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Remote Sensing of Earth Resources System Capabilities V.S. Design Constraints

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REMOTE SENSING OF EARTH RESOURCES
SYSTEM CAPABILITIES V.S. DESIGN CONSTRAINTS

BY

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ABSTRACT

There is new evidence that a global earth resources satellite net will be practical. This paper weighs recent advances in remote sensing to pinpoint the dominant constraints. The data and senser systems interfacing requirements are critically reviewed. It is shown that conventional optics constraints can be relaxed, with the newer systems, based on multi-spectral imagery and statistical processing methods. The most powerful computational methods use algorithms based on a Gaussian assumption for the species vector in feature space, but biases in the imagery limit their efficiency. A rationale is proposed: improving the observational network calibrating efficiency will also improve the photogrammetric removal of imagery biases, and thereby increase signature detection efficiency. The author discloses an unexpected finding: while conventional resolution degrades with satellite altitude, signature detectability should improve since calibration improves dramatically with altitude. A unique global network is then described that can exploit these new developments.

The scope of this subject is so broad that despite the paper's length (sixty pages), a quantitative treatment is not practical; the author uses a combination of classical analysis, bibliographic research, and conservative technological assumptions based on the current state-of-the-art.

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I. INTRODUCTION

General

This paper addresses the constraints and design status of remote sensors for environmental monitoring; the viewpoint is present status v.s. announced or intended purpose. In order to appreciate the functional purpose of Remote Sensors for Earth Resources, it is necessary to look at the overall functional purpose of the Earth Resources System. Only from a systems viewpoint is it possible to evaluate sensor capabilities. The sensor is actually only a very small element in the overall scheme, although the state-of-the-art in sensor development has a critical impact on the system capabilities and development. It is the purpose of this paper:

- to explore the current state-of-the-art from a total systems viewpoint.
- to identify the most promising developments in sensor hardware and supplementing software.
- to project the probable trend.
- to make certain limited contributions intended to be consistent with improving systems capability.

Evaluating the Earth Resources System

The Earth Resources System (ERS) is a Management Information System (MIS) in the classic Sense of an MIS, as explored by the very extensive MIS literature. Blumenthal's excellent book (19), is a comprehensive treatise on these problems, while MIS misconceptions, pitfalls, etc. are quite well summarized by Ackoff's short article (20). Potentially, ERS is the largest MIS ever designed; we are addressing a global subject with multiple layers of interaction: agriculture, minerology, meteorology, hydrology, oceanography, geology, cartography, etc. Therefore, the first concern is to identify an appropriate MIS framework designed to keep the huge ERS data stream manageable (by filtering, editing, preprocessing, etc.). This presupposes that we clearly understand the data systems taxonomy (with its functional units, data systems modules, and decision-activity elements). This also demands appropriate decision models for control, as well as the more scientifically interesting process detection (math) models for the identification of state (inventory).

In short, the ERS information system has the same man-machine interface problems and challenges as any other MIS, except the field is newer, more poorly understood, and larger than any MIS in history. All of which leads to a first conclusion, as emphasized repeatedly by the experts (Blumenthal, et.al.), that the MIS development should proceed carefully in small, discrete, evolutionary phases. However, again as Blumenthal warns, this does not justify a "develop now and integrate later" attitude. It is critical, and even an economic dogma, that the MIS must have a cohesive framework that is capable of evolving into the global MIS <u>at the start</u>. And every evolutionary MIS phase must adhere to a framework that evolves in manageable steps. The sheer magnitude of the potential data stream, from a global ERS satellite network is so staggering (10^{10} to 10^{20} bits/sec) that it would be inexcusable to start up a huge MIS to be scrapped later because of a lack of framework planning. Then the first business at hand, is to plan the framework for a first generation MIS that has the needed growth (by evolution) attributes.

Rogers feels (3) that our ERS community is already "in trouble", so far as formulating reliable, and objective decision models. He points out that as the data base grows, without appropriate data quality, editing, and filtering, that the possibility of mismanagement is growing also. In short, too much irrelevant data can be worse than not enough data. Rogers also warns of the need for close integration of subsystems, and the need for planning controls to assure that we are addressing an economically viable development. This does not imply that potentially viable projects are difficult to find. Cost-benefit analysis of irrigation hydroelectric, and pollution control projects (for example), have shown adequate economic justification for developing a hydrological data subsystem for the ERS/MIS. This latter situation even applies to the underdeveloped countries, who can least afford the costly mistakes of "changing MIS horses in midstream."

Therefore, this background or overview of the total ERS mission, as a giant, global, multi-layered information network, will be the yardstick used in this paper to explore the current ERS state-of-the-art. For example, this yardstick will be used to evaluate the relative merits of aircraft, v.s. "in situ" (data collected at the site), v.s. satellite collected data. Another example is the compromise between sensor platforms at low altitude (for data with high spatial resolution but wide field of view) v.s. high altitude (lower resolution, but a more synoptic data base). This too can best be evaluated from the objective viewpoint that the ERS is economically justified as a global MIS.

Evaluating the Sensor Subsystem

Again, from the MIS viewpoint, we are interested in a Sensor Subsystem that results in maximizing the probability of detection. Holter

(6) points out that, contrary to popular opinion, in some cases a low spatial resolution sensor may give better detection reliability than a high resolution sensor. Doyle (7) uses the term "detectability," as this sensor-detector-analysis subsystem attribute. He shows that it is highly dependent on <u>contrast</u> and <u>continuity</u> of the signal, as well as <u>frequency resolution</u> and <u>spatial resolution</u>. He notes that a long lineal feature, such as a pipeline, can be detected when its width is only 10% of the so-called Rayleigh optical resolution limit: $\theta = 1.2D/\lambda$

where θ is angular resolution in radians.
D is the aperture diameter.
λ is the wavelength of the detected spectral component.

Clearly, in the case of the pipeline, signal continuity and contrast are the critical parameters affecting "detectability." A star on the other hand is certainly <u>not</u> spatially continuous, but its great contrast is the key criteria in detectability, since a star can be readily detected even though it is orders of magnitude smaller than the Rayleigh "limit." Holter emphasizes this point by noting that no matter how finely we resolved a black cat on a black rug, without contrast the detectability of the target (the cat) is nearly zero.

This basic argument is behind the interest in multi-spectral sensors. Every species has a variable frequency v.s. intensity continuity profile; usually the spectral range of interest runs from ultra-violet down to the far infra-red. Within this range, the particular species will have spectral bands were its reflected or emitted intensity will be markedly different (high contrast) than an associated species. This difference can be used to advantage to improve the detectability. By comparing the species spectral profile (called the species "signature"), with a "known" profile, automatic recognition by computer processing is possible.

Doyle notes that other authors have shown that about three to five resolution elements (discrete spectrally sampled points) are needed to determine whether an object is a square, circle, or triangle. Hoffer (13, 14) notes that Purdue University's computer system detection results don't improve significantly when more than five elements are employed, although the costly computer time (t) goes up drastically as the number of elements (n) increases. The time for one element (a) increases approximately as: $t = a^n$. From these results, we can conclude that an initial MIS for a global ERS, should provide for: at least <u>five</u> high <u>contrast</u> spectral <u>bands</u> (for <u>continuity</u>) of sufficient spectral and spatial <u>resolution</u> to separate the species of interest. Since each species has a unique "best" set of bands, then the ERS should provide perhaps twenty bands (from which the pre-processor will select the five "best"). Also, since detection is a statistical inference process, we should again emphasize the necessity of sensor (hardware) and computer (software) integration.

In the following sections, sensors, sensor platform, and software characteristics are explored in greater detail. However, to put "first things first," throughout this paper we will try to emphasize MIS design for <u>detectability</u> of high payoff areas of ERS interest (hydrology, meteorology, air pollution, agriculture, minerology, commercial fishing, etc.). Therefore, we will review software progress <u>first</u> (in the next section) so that a more meaningful analysis of sensor performance and sensor platform characteristics can be identified. This may seem to be a reversal of the usual approach: "design the hardware first, and then design the software to fit." Nevertheless, our consideration of ERS as a huge MIS, points to the advisability of considering the software constraints (the signature identification problem) as the most critical overall "driving function."

II. DATA PROCESSING

General

The information needed for earth resources is multi-dimensional and multi-disciplined. The "eyes", or data acquisition source, for the system are numerous, but the most effective source is from satellite sensors, since these supply the synoptic overview data, that control of this information system demands. The physical phenomena disciplines are: geology, hydrology, forestry, oceanography, agriculture, meteorology, minerology, etc. From this (partial) list, it is obvious that this information system envisions a tremendous data base file feeding numerous information subsystems that are data base files systems in their own right. Clearly, there is danger here for the MIS design, as well as a challenge of unprecedented magnitude. The danger is in providing too much unnecessary, poor quality, ambiguous data to the user. The challenge is the management of information over a global service for man's most important economic activities, which implies the ultimate design of the largest MIS ever proposed.

A Typical MIS for ERS

The scope of this paper prohibits even a first cut MIS appraisal of the overall system. Therefore, as a demonstration of one such MIS within a single class (agriculture) of the many applications, a system used by one user will be described. This system was developed by the Laboratory for Agricultural Remote Sensing (LARS) at Purdue University; the MIS software package is known as LARSYS.

The user for LARSYS, is typically an agriculture research scientist, or botanist, with some expertise in FORTRAN IV, but with very little appreciation of the MIS design, data quality management, system modular interface problems, etc.

LARS users and computer systems personnel recognized that in order to develop an agricultural species signature data library, that very close man-machine coupling must be maintained. The computer "learned" each specie pattern (throughout a period) as the analyst compared spectral response with ground truth data. Therefore, the systems designers recommended that a conversational mode be used. Also, development of the data processing hardware and software was given a high priority, and placed on a level with the biogeophysical remote sensing, and measurements requirements. Despite these proper precautions, however, the tremendous data stream placed severe constraints on the MIS design, and results to date show that it was probably the most serious constraint on the project.

The Data processing program was subdivided into the major segments described in this diagram:

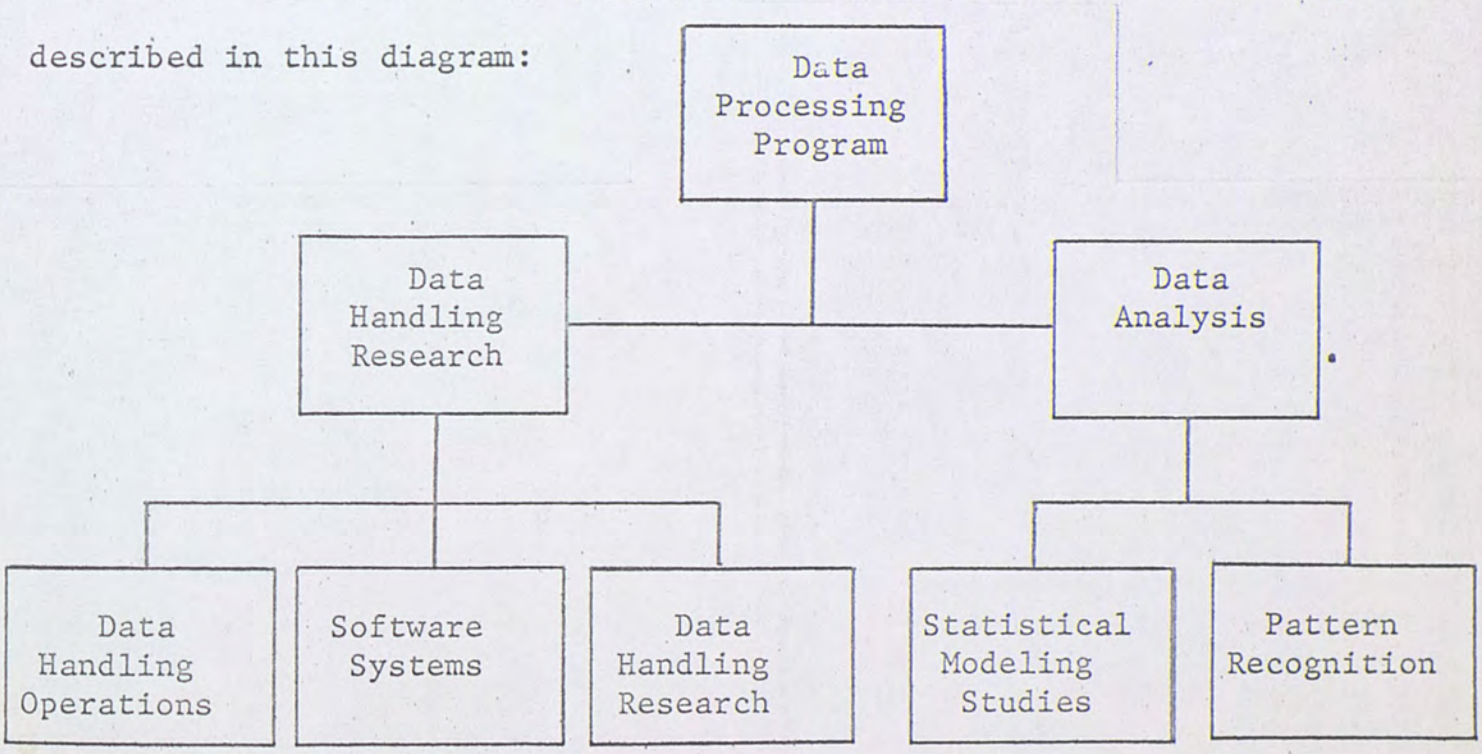

FIGURE 1. Data Processing Program

The scope of the user's requirements are outlined in these three charts below, which show the Measurements, Remote Sensing, and Agricultural subsystems.

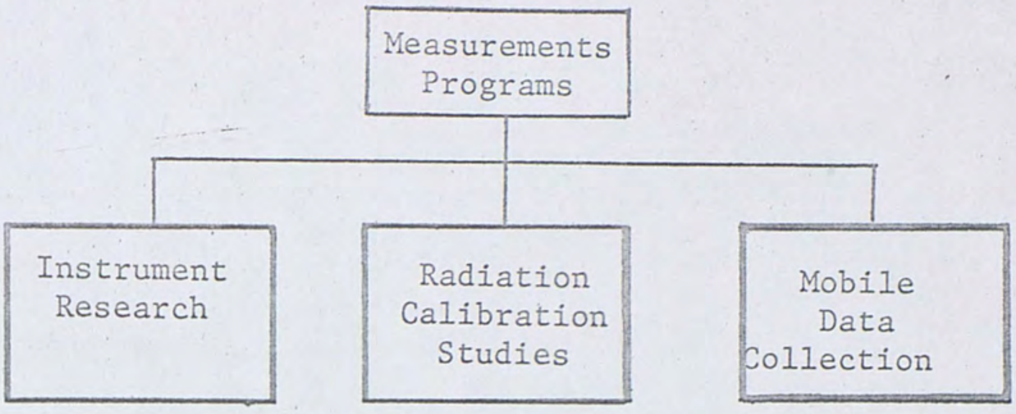

FIGURE 2. Measurements Subsystem

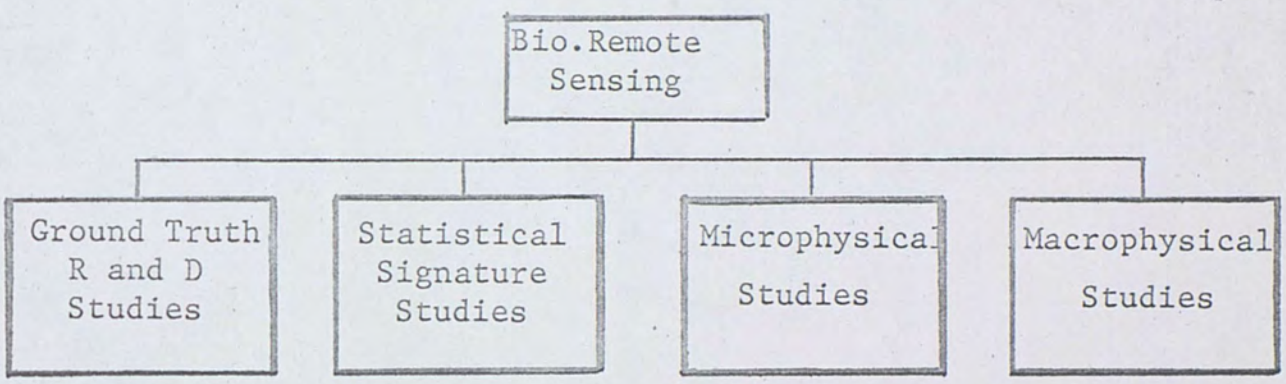

FIGURE 3. Remote Sensing Subsystem

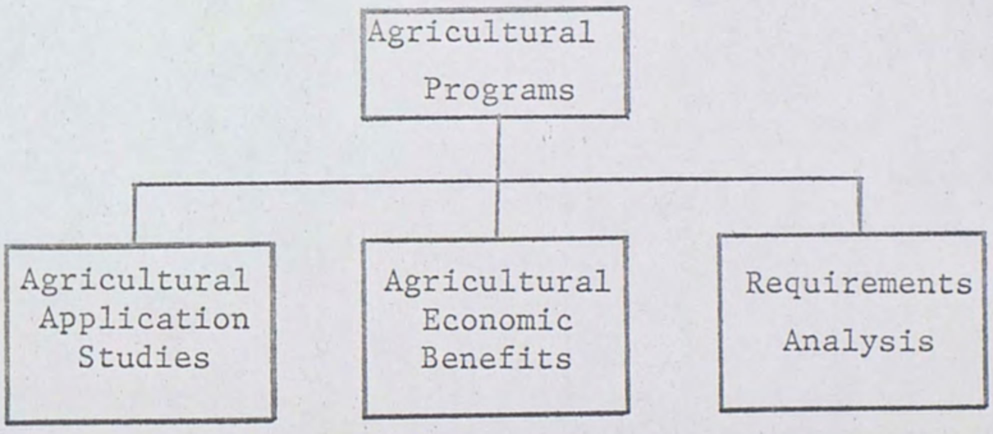

FIGURE 4. Agricultural Subsystem

The systems (design) and user (requirements) team agreed on this systems objective:

1. Data quality maintenance demands spectral and mensurational calibration of the data, before being admitted to the particular investigators program (upstream of the functional modules).

2. Data must be reformatted according to each users need (filtered, compressed, edited, etc.).

3. Ground truth (specie signature state in data file) data to be stored in near optimum fashion.

4. Flexible interfaces between modules be provided so that each researcher have a wide ranging, efficient data file.

From the very start of the project, people with MIS skills were teamed with the research staff; as teams they were integrated into the overall project development chain, and participated in recommendations for systems specifications for systems improvement (the evolving MIS concept). Continuing efforts were made to improve man-machine communication efficiency.

Major subsystems, within each category were identified; these are interesting in that each subsystem breakout was clearly compatible with a different MIS component package design. For example, the Remote Sensing Project (Figure 3), has these subsystems:

1. Feature selection

2. Training sample selection

3. Delineation of categories

4. Pattern classification by algorithms compatible with high data volume.

A turn around time of 48 hours was set on the system to assure data acquisition, and analysis before ground environmental conditions could change appreciably. Initially, graphic printouts were extensively used, but as the efforts to minimze turn around time materialized (the

MIS evolved), an improved I/O was installed; this improvement was a digital image display so that the researchers could retrieve and display graphics for pattern learning by man experimentation and machine analysis results display. This system is an Optimization Model, since a "best" prediction from computer displayed prediction is "learned" by the computer via man-machine communication. It is the reverse of machine aided cognition, since in this case it is machine aided to man, followed by man to machine aiding of cognition. The LARSYS is therefore a very advanced example of placing the user "on line" in the conversational mode.

Previously, in Figures 1 to 4, project functional responsibilities were shown. In Figure 5 below, the data processing subsystem structure is shown:

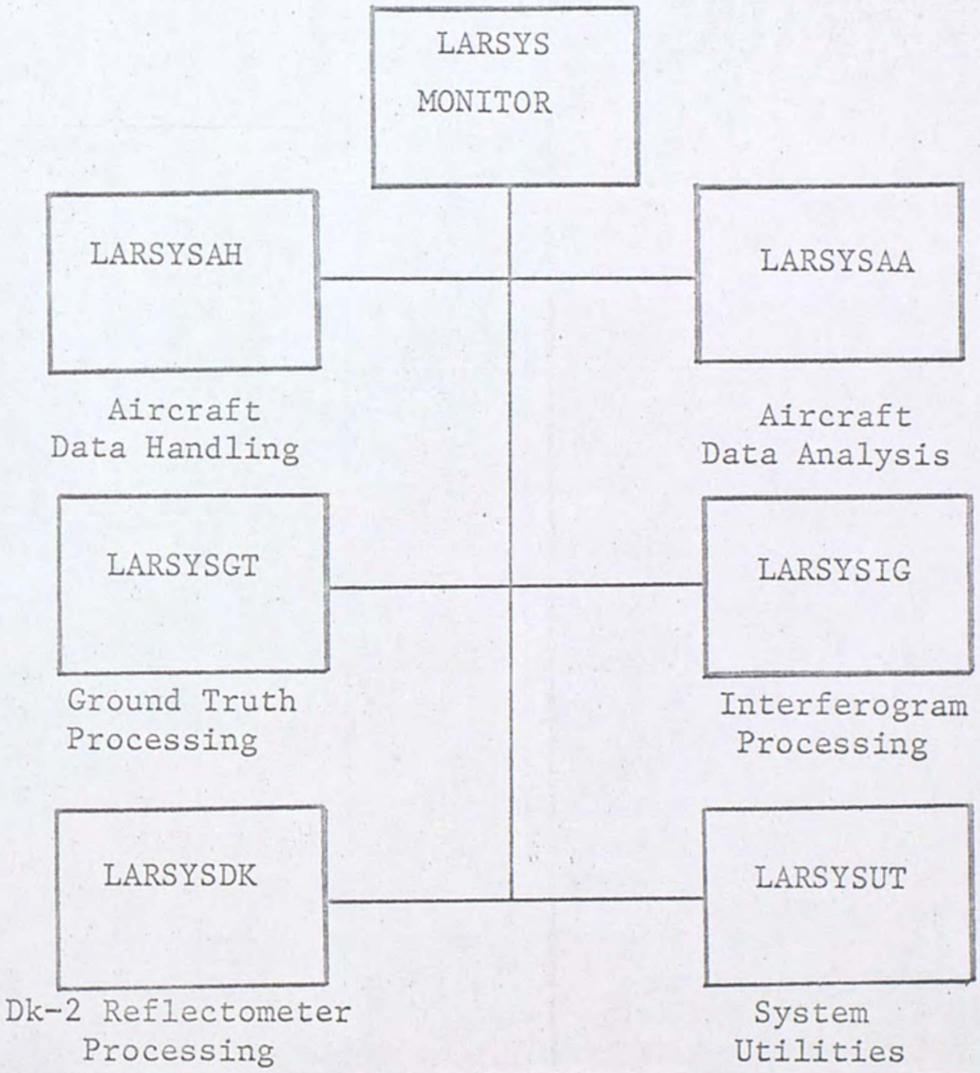

FIGURE 5. LARS Programming System (LARSYS)

As can be seen, these subsystems are broken out along functional and even geographical lines for assignment to a project engineering type approach. One of the functional data processing projects (subsystems) is further described down to the modular level in the figure below. We will discuss details of the statistics processor, and the classification processor, later in this section.

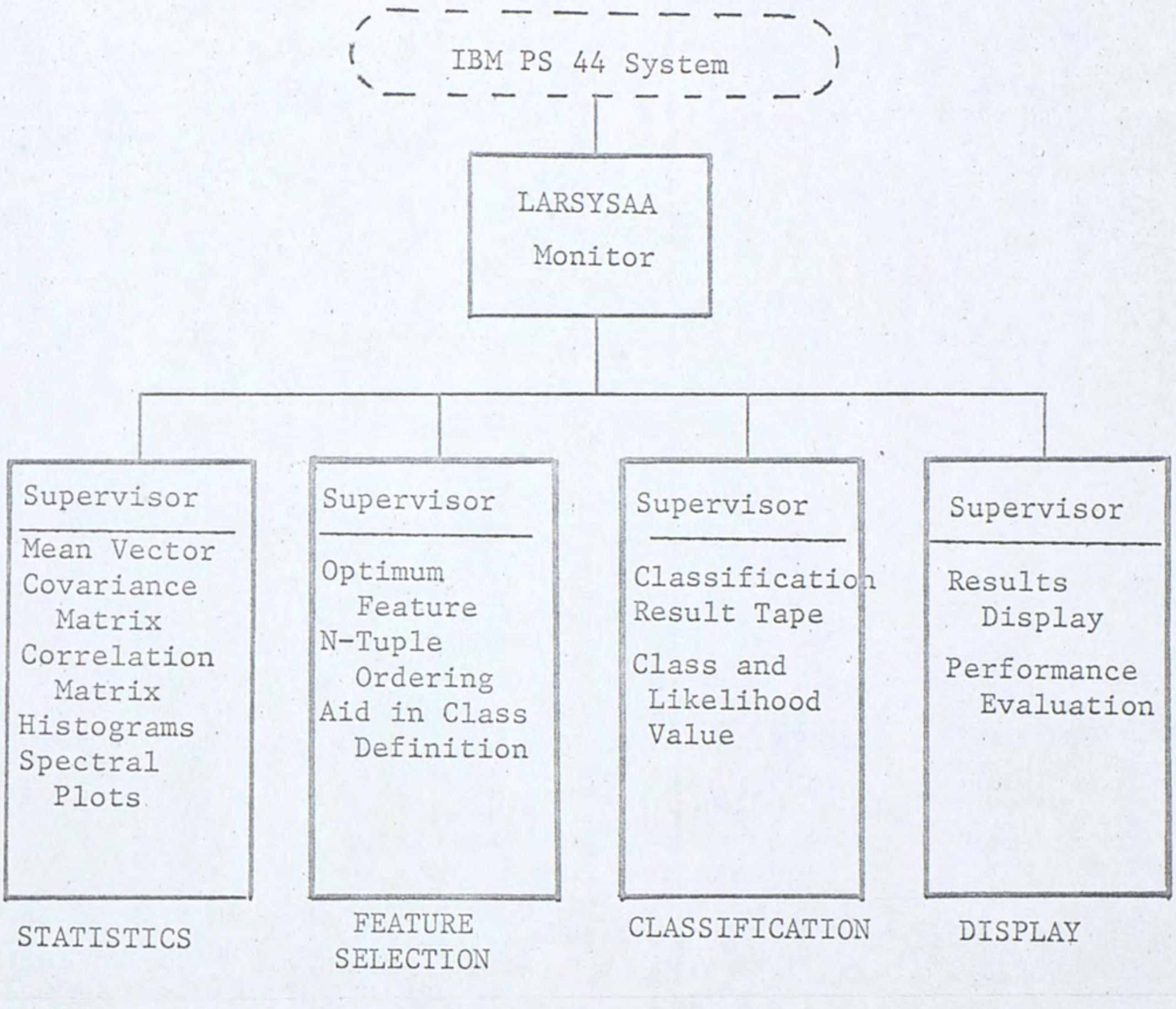

FIGURE 6. Aircraft Data Subsystem

Certain details of the system design are particularly interesting. The user-system interface received considerable attention by the data systems designers. The reasons for this were threefold:

1. Optional classifier design required substantial interactions during each of the various phases of the classifier development.

2. Satellites and aircraft, viewing vast areas, with high resolution, multi-spectrally, generate a staggering data stream. This leads to demands on computer time. Therefore, data quality and editing is of utmost importance early in the user-machine communication for classification, since errors in later stages with multiple parameter statistical regressions would cause severe penalties in computer time.

3. The experimental nature, of the classifier man-machine communication and learning optimization process, and the backgrounds of the researcher users, requires a high level compiler language. This makes for ease in program modification as the system evolves.

The LARSYSAA System Monitor uses a program system compiler that has features that are at even a higher level than FORTRAN IV. The LARSYSAA compiler uses a code followed by key words, with errors sensed and immediately communicated by type out to the on line user. This rapidly speeds up the learning process, since the format is almost free-form card input.

Due to the extremely flexible operation, the processor supervisors are set up for dynamic memory allocation, as well as interpretation of control cards ("keyword" I/O interface), and the usual processor control function.

Finally, a list of LARSYSAA processing programs are recorded below in Table I as evidence of the size of the overall MIS. Each program can be considered to be a module; there are about 20 in the LARSYSAA.

TABLE I

LARSYSAA PROCESSING FACILITIES

Statistical Analysis Facilities

Compute mean vector and covariance matrix for each class.
Compute mean vector and covariance matrix for each field.
Punch data deck containing statistics and other pertinent information for future use with Classification Processor.
Histogram selected features for each class.
Histogram selected features for each field.
Print spectral plots for each class.
Print spectral plots for each field.
Print as many spectral plots as desired, each displaying results for up to four different classes.

Feature Selection Facilities

Determine optimal sets of 1, 2, 3, ... features.

Classification Facilities

Perform pattern recognition using any subset of classes and features made available by the Statistical Processor.

Display Facilities

Print information as to source of training data.
Outline training sets if they appear in results display map.
Print results of training operations.
Use a specified symbol set for results display map.
Compute and print classifier performance evaluation for training set
1. on per class basis
2. on per field basis

List areas used as test samples for performance evaluation.
Outline on results map the areas used as test samples.
Compute and print classifier performance evaluation for test set.
1. on per class basis
2. on per field basis

Apply likelihood thresholding to establish a rejection class.
Recompute and print performance evaluations on the basis of any specified grouping of classes.

Statistical Basis Of The LARSYS Statistics Processor

Each data channel (of perhaps 21 spectral channels in more advanced aircraft sensor systems) responds to the target object with some particular response magnitude. Since each sensor channel samples a portion of the optical spectrum, then each channel represents a magnitude and wavelength response. For two channels, at wavelengths λ_1, and λ_2, sample vectors $\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$ might cluster in (λ_1, λ_2) feature space as shown below,

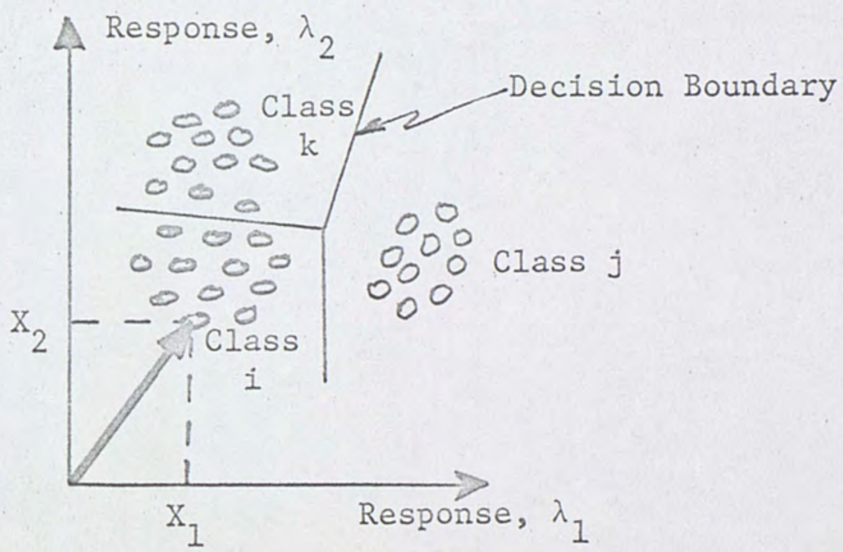

FIGURE 7. Specie Vector in Feature Space

Since the data for each species forms a cloud of points in feature space, and since these point clouds tend to overlap, a method of separating them with "decision" boundaries is needed. Several approaches are used.

P. H. Swain, of LARS, Purdue University (11) describes the algorithms as largely statistical in nature, although in some cases "known" specie patterns are "learned" by the computer. An important assumption is that each pattern distribution is statistically normal, so a multivariate Gaussian model is used. That is, LARSYS works under the assumption that a mean vector and covariance matrix are sufficient to characterize the probability distribution of any pattern class.

The probability of x_i (in a one dimensional case) would be represented as:

$$p(x_i) = \frac{1}{(2\pi)^{\frac{1}{2}} \sigma_i} \exp -\tfrac{1}{2} \frac{(x_i - \mu i)^2}{\sigma_i^{\ 2}}$$

where μ_i is the mean, and σ_i^2 is the variance for class i. For the multivariate vector X_i case, μ_i becomes a vector U_i (to the centroid of the data "cloud"), and $\sigma_i^{\ 2}$ becomes the covariance matrix Σ_i. Then $P(X_i)$ is represented as:

$$P(X) = \frac{1}{2\pi |\Sigma|^{\frac{1}{2}}_{det}} \exp -\tfrac{1}{2}(X - U_i)^T \Sigma_i^{-1} (X_i - U_i)$$

This forms the basis for the statistical processor.

The classification processor (see Figure 6) establishes the boundary. It uses Bayes Rule and algorithms for introducing (apriori) boundary conditional probability decisions by either operator decision or computer "learning" by scanning a "known" or "ground truth" image. The LARS method is statistically sound if the data is unbiased, but the Bayes Rule Method is even more sensitive to the statistical independence of data channels. This classification method is known as the Maximum

Likelihood Criteria.

An interesting variant is used by the University of Kansas, known as the "clustering algorithm." The distribution of a specie signature in a three dimensional (for example) feature space will be an ellipsoidal cloud (it can be shown to have this shape if the statistics are Gaussian). The method finds the centroids of the ellipsoids for each class (i, j, k) and computes separation distances. Next, it selects a different configuration from the $(\lambda_1, \lambda_2, \ldots \lambda_n)$ channels, and repeats until the maximum least squared configuration is found. This is the "best" configuration for detectability or species discrimination. Note (again) that the Kansas University technique depends on the gaussian assumption. But the computational time can become excessive. Consider n species, and m channels, constrained to a 5 element vector in feature space (arbitrary). The number of cycles of calculations needed are: $\frac{n!\ m!}{5!}$. For example, if 8 species are to be identified from a 12 channel sensor, $\frac{8!\ 12!}{5!} = 1.6 \times 10^{10}$. Of course, short cut methods are used, with limited success, to reduce this problem. However, the reader should realize that the statistical nature of the data has the greatest bearing on the computer time needed. Again, this shows that very careful and comprehensive pre-processing of the raw data (filtering, editing, quality control, calibration, etc.) is an absolute necessity for a viable MIS.

Considerations For A Global ERS/MIS

LARSYS, developed at Purdue University by their Lab (LARS), concentrates on answering the questions "what," "where," and "when." That is, as presently constituted, the LARSYS is only the agriculture inventory step for the total ERS management system. Ideally, LARSYS makes a determination of the amount and quality of each type of agricultural earth resource that is a candidate for management. But for a total management system, the ERS Project must implement the three step process: inventory, analysis, and operations control functions for all resources. These functional flows must in turn be monitored and paralleled by appropriate MIS channels.

In the inventory step, accurate determination is made (amount and quality). In the analysis step, management decisions are made with respect to these resources by considering inventory v.s. cost-effective or cost-benefit ratio goals of management (governmental policy, etc.). In the operations step, decisions are implemented by action on the resource (water diverted, crops planted, etc.). Then a complete Earth Resource Management System must either model a decision flow methodology or provide data germain to decision making. One example of these decisions, is whether or not to use pesticides and fertilizers in view of the conflicting needs of agricultural interests v.s. large scale degradation of the environment due to extensive use of these potentially dangerous chemicals. For this function and others, optimization models are needed.

Towards preparing an appropriate management decision model (for a total MIS), the "system" response time becomes an important criteria. Meteorological and hydrological phenomena are so dynamic that a response time in hours or minutes is necessary. Some resources are cycled about twice a year (i.e., a tomato field), and some are renewable in about 10 years (e.g., certain forest crops), while some can never be renewed (e.g., mineral and fossil fuel deposits). Other dynamic forces include the creeping spread of asphalt and concrete, the clearing of virgin land, etc. Therefore, the management decision process for earth resources has to be modeled dynamically in keeping with the reality of these forces.

The decision process necessarily implies a prediction model. For example, from monitoring agricultural crops ('ala' LARS), the agricultural community should be able to predict and forecast labor requirements as a geographically dynamic entity (moving from the south in the spring, to the north in the summer and fall, etc.). Similarly, such information and decision flow could be used to economically control the food-processing industry, transportation, etc., to keep production in balance with demand (economic demand and supply decision factors), the labor supply, capital, and supporting industries.

There are numerous examples of decision models that are simple, but were impractical to implement prior to the ERTS project, and current development of inventory type MIS's such as LARS (i.e., work at University of Michigan, University of Georgia and Kansas, etc.). For example, fish and wildlife agencies are interested in stocking fish. Their economic decision model relates to geography (local to the user), transportation costs, and water temperature profiles since game fish are critically intolerant of high temperature. Infrared sensors from ERTS (and NIMBUS) satellites, provide this data base, so that conceivably, this data could be made available in the ERS/MIS to the subsystem serving this user. Another user, the state pollution control office, will need water temperature, hydrological parameters, benthol distribution, etc., from such a system. Man-machine interfaces for this user might be graphic display or print-out of lakes with temperature and chlorophyl contour overlay, etc.

Comments On Needed Improvements

Feedback is of course an important action in any MIS's evolutionary development. For example, data for the LARS system, from multispectral photography was so extensive (too much superfluous data is a cardinal MIS "sin"), that editing, or filtering techniques, became critical. The users recommended changes (the feedback, for MIS evolution step) that would isolate (filter and condense) phenomena that pertained to the user. The result was the subsequent development of edge enhancement techniques, contrast enhancement, and automatic species classifiers using statistical methods (maximum likelihood criteria of the spectral signature).

We should next address a critical problem that impedes the further improvement of the data quality (upstream to the classifier). Without exception, the software developments (University of Michigan, Kansas, Georgia, and Purdue) are based on a Gaussian statistical assumption for the data "noise," i.e., filtering by statistical normal methods are used. Such methods are reliable only if the statistical distribution is normal, but in reality the distributions are skewed by data biases. Experience in Aerospace mensuration data analysis in the 60's, led to some remarkable advances in bias determination techniques. These methods will be most important to ERS, since the data "glut" is still the most serious MIS problem.

In reference 10, a technique developed by the University of Michigan is described that can detect up to 10 different species within a single resolved element (instantaneous field of view, of the scanning spectrometer). This very advanced technique depends (again) on data with a Gaussian distribution. It is most critical to the reader's understanding, and appreciation of the interface here between hardware and software, that if data biases can be removed, so that the Gaussian assumption will be valid, detectability will be immediately improved 10 fold! Extrapolating similar aerospace experiences, and Michigan University's data, we can expect a 100:1 improvement in detectability in about 10 years of development (of precise bias determination techniques, etc.). Oddly enough, this means that calibration techniques are the key to sensor detectability. Therefore, digital calibration is a critical factor in overall sensor systems performance.

Calibration of Systematic Errors*

As we've mentioned before, data is not information until it has been edited and filtered. To remove systematic errors (biases from non-linearities) from the sensor data, this means we must:

1. Detect and remove data transmission errors,

2. Detect and remove systematic errors due to non-linearities in propagation, transfer function of the sensor and detector,

3. Isolate and filter the data such that appropriate data is admitted to the software module.

Currently, systematic errors are partially removed by pre-processing of the raw data. For example, ERTS Data is pre-processed at NASA's Goddard Space Flight Center (GSFC); we will assume that NASA's techniques are representative of the current "art."

A distinction should be made between analytic evaluation and calibration. The evaluation of a sensor (system) data channel (s)

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*Duane C. Brown, an internationally recognized authority on the calibration of sensor derived data, is referenced here without detailing his numerous writings as the literature is replete with his contributions.

consists of the determination of the phenomena measured with emphasis on performance against system specifications. The central objective of evaluation is to determine if the specification criteria are being met. Generally, even the most rigorous evaluation proceeds no further than the separation of random (Gaussian statistical) and systematic error classes. It does not address the problem of separating systematic errors by type or species (propagation, optical, electrical, etc.).

Calibration begins where evaluation leaves off; the central objective is to uncover and explain the source of the individual systematic error sources. Calibration seeks to describe a systematic error model so that appropriate corrections can be made to (each channel) the observational data.

The pivotal concept in any process of calibration through data analysis, is the error model. The usual (conventional) error model considers only a zeroing error, or constant bias in each data channel. For example, in the lab, a technician zeroes a volt-meter against ground, and "calibrates" full scale against a "known" standard. However, realistic error models must now be considerably more complicated than this in light of the non-linearities in the total systems transfer function. The popularity of <u>linear</u> techniques (Laplace transform, etc.), should not keep us from recognizing that a real system is <u>non-linear</u>.

The process of calibration can be accomplished by one of the following methods:

1. A "better" performing instrument (which is the "standard") is the basic model.

2. Special tests for individual components.

3. A data analysis is used to determine internal consistencies.

4. An "apriori" error model is constructed by systems engineers in conformance with the design. These apriori assumptions are usually based on a complex but linear model.

5. A statistical fit to a generalized error model is used by utilizing numerous data channels, with sufficient data channel redundancy to assure determinancy of the more extensive model.

The most satisfactory method is actually an evolutionary combination of methods 4 and 5. Where statistical certainty identifies error coefficients, they are more easily (and rapidly) removed by classical analytic models (Method 4), leaving fewer unidentified biases embedded in the data for subsequent analysis and identification by Method 5. After (perhaps months) a period of time, another "breakthrough" in identifying another bias contribution is achieved and so another error coefficient is modified for the next stage. This method envisions the process as one of continual improvement, which is simply a commentary on the truth that the real world data is approximated ever more closely by the finite term representation of the error model. As an aside, we note that this is consistent with Blumenthal's view on the evolving MIS.

Goodness of fit is not always a criteria for evaluating the performance of the error model. For a single data stream, over perhaps a given trajectory (as for example a satellite pass), a regression analysis to fit the error model to the data could most likely result in a near perfect fit. Unfortunately, on a subsequent pass, with different geometry, the derived error model would be worthless, as the systematic errors change with the orbit, scene, attitude, range, etc. Then goodness of fit is a necessary, but not sufficient, criteria. Only when the geometry, dynamics, etc. have exercised the sensed data streams over all expected excursions, so that each independent variable in the error model has been statistically exercised, can goodness of fit be relied on as a necessary and sufficient criteria.

Certain data requirements are implicit in these rather massive regression analysis data reduction techniques. The multiple term error models used, require multiple independent data channels, in order to get convergent solutions. The key to using these very powerful techniques is adequate data redundancy and the data channels should be independent. For example, a sensor data stream from two satellites moving in perpendicular, or orthogonal orbits, would have systematic error effects (from doppler) that would be decoupled, or independent.

Satellite Nets and Software Trends Will Expand MIS Bounds

In summary, we conclude this section with these four observations:

1. The pre-processing done at NASA/GSFC is an adjustment of imagery to "apriori" assumptions based on geometric optics principles (8, 9). As such, it only complicates a truly rigorous adjustment of the raw data.

2. The signature analysis methods used by LARS (and others) accepts NASA's "corrected" imagery, then digitally filters lower spatial frequencies out "because of biases." The resulting midband frequencies are then assumed to be bias free. The signature recognition algorithms are based on Gaussian statistics, which is of course invalid if the distribution is in fact skewed by biases. Similar comments must be made of software at the University of Kansas, Georgia, Michigan, etc.

3. A new hardwired ERS analysis system (built by General Electric Company at Daytona Beach) may be reaching the detectability limit of biased imagery. General Electric's "System 100," permits of skewed signature distributions. However, this is derived by a "goodness of fit" algorithm developed by General Electric, with no attempt made to identify the error coefficients for correlating imagery at different times, flight path, lighting, etc. This violates one of Brown's (above) bias determination principles, but for scene by scene analysis, and "ground truth" extrapolation, this is indeed an advance. However, with ERS systems planning and design, much better MIS performance is possible. Scene by scene extrapolation is not practical for a globally automated ERS net, as it requires repeated "relearning" of the ground truth replica for each new image, as lighting, aspect angle, etc. changes.

4. An overall satellite network design is needed that is strongly calibratable. Since this is not practical with present ERTS coverage, we will develop criteria for such a network of satellites in the next section. When multi-spectral optics are integrated with appropriate calibration software, the detectability of the total MIS may be as good from satellite altitude as that now possible from aircraft. Also, aircraft imagery detectability improvements may depend on these developments. In short, for multi-spectral ERS, the sensor's physical optics Rayleigh resolution "limit" will be expanded by software, proportionate to the calibratability of the satellite net.

Quoting from Reference 10, the fastest computational algorithms can be used only "when the covariance matrices of the pure signatures are scalar multiples of each other." This same paper notes that "when the covariance matrices are large relative to the dispersion of the means, that the species estimates (within a single spatially resolved field of view) are poor." Again, this paper shows a 10:1 difference in computer processing time when the data permits the faster algorithms to be used, and even greater computational leverage is being promised. Then the number of species resolved in a given processing period (that MIS "yardstick" again) is strongly dependent on the condition of the covariant matrix, i.e., dependent on the removal of the biases embedded in the data (which couple to the covariant elements).

Therefore, there must be an optimum altitude for multi-spectral ERS, since it can be shown that calibratability (and so detectability) <u>increases</u> with altitude, while spatial resolution <u>decreases</u> with altitude. As altitude increases:

1. Orbital stability increases.

2. The orbital observation span increases, so that the orbital constraints in the error model are more completely exercised.

3. Tracking becomes denser (more overlap and so more independent data channels).

4. Observational geometry improves (longer base lines, etc.).

5. Imagery overlap increases, which will improve rigorous photogrammetric block adjustments.

6. A narrower field of view will cover a given area, so that edge distortion will be eased.

Using multi-spectral imagery and the new computational methods (10, 11, 14), geometric distortions that cause misalignment of the axis of the instantaneous field of view (FOV) will degrade signature recognition accuracy more critically than non-linearities within the FOV. Calibration of both of these bias sources to a common datum (for the multi-spectral channels), are particularly sensitive to the above six criteria. Therefore, MIS detectability should improve dramatically with altitude despite the degradation of spatial resolution from a physical optics viewpoint.

In simpler words: although what <u>we</u> see with our eyes gets worse with altitude (or distance), what the <u>computer</u> "sees" should increase to a peak near the altitude where system calibration potential peaks. This is a technical surprise as our senses and conventional optic principles tell us just the opposite. The discovery of this unexpected fact and its systems implications are probably this paper's most important <u>new</u> finding and contribution.

III. SENSORS

General

Remote sensing is the science and art of acquiring information (about earth resource species) from measurements made at a distance (without coming in contact with the species). Information is transmitted from the target (species) to the detector (observer or receiver) through magnetic, gravity or electromagnetic fields, and in particular through the spectral, spatial, and temporal variations of these fields. The sensor must be able to measure the variations of these fields.

The electromagnetic fields, are the fields with the greatest potential utility. In Figure 8 below, we want to call attention to the optical wavelength spectrum, as recent ERS data has come mainly from this sector. Although, we are more familiar with the visible light part of the spectrum, since our eyes are sensitive to that band (0.4 to 0.7 μm), there are significant species signature variants <u>outside</u> the visible band.

The measured parameters are:

Wavelength - Spectral
Shape - Spatial
Polarization - Vectorial
Time Change - Doppler (Fast) - Time Lapse (Slow)

Optical, Infra-Red, and millimeter-wave radar instruments are the sensors of greatest interest. Some of the more desirable attributes for these instruments are:

High spatial resolution,
High spectral resolution,
High sensitivity (high signal to noise ratio),
Wide band pass transfer function,
Known, stable, and/or determinable transfer function of optic and electro-mechanical components, detectors, converters, etc.,
Temporal stability, and fast response time,
Digital format compatability.

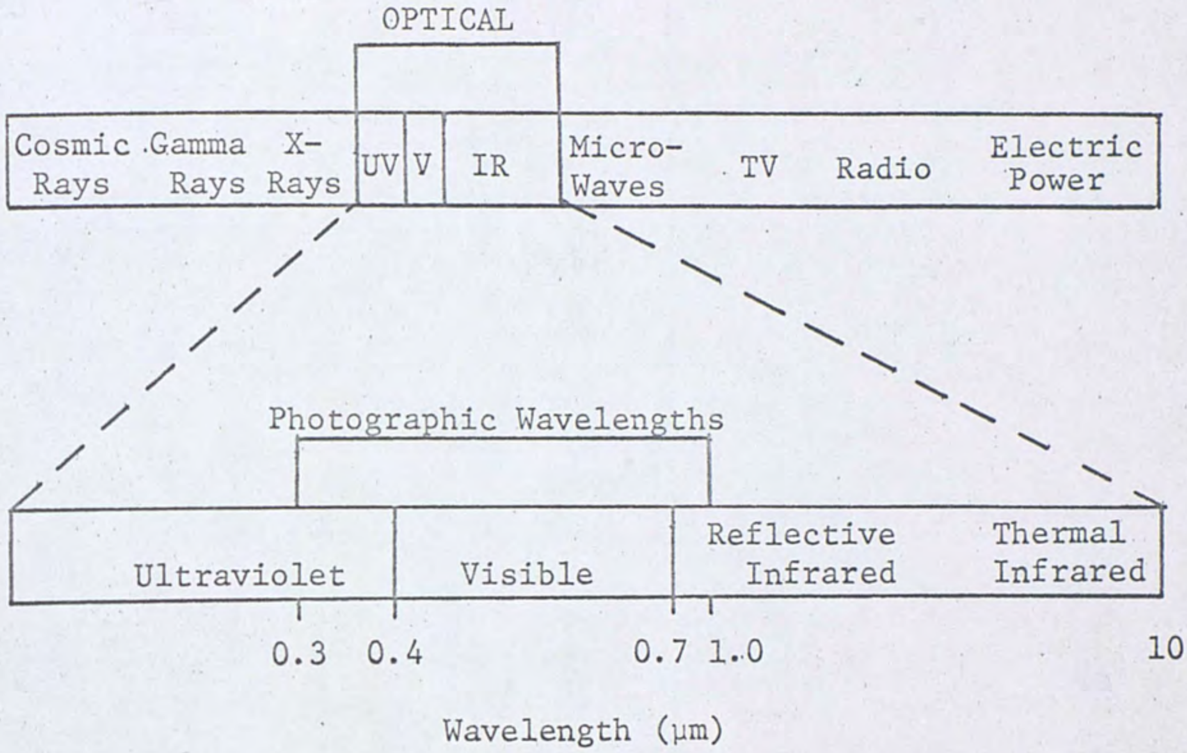

FIGURE 8. The Spectrum of Interest to ERS

System Considerations

Landgrebe (2) classes sensor systems for ERS into two categories: (1) the conventional photograph or image orientation type for analysis by photo interpreters, and (2) the numerical orientation type for digital analysis and interpretation. In the latter case, the system is capable of digital pre-processing and detection in the machine-aiding mode (from the MIS viewpoint) without first using an analog to digital conversion device (as needed by the image orientation system). Examples of the former are camera (including multi-spectral cameras) or video tape TV. Examples of the latter are multi-spectral scanners, and Return Beam

Vidicon (RBV) or digitally sampled (grey code, etc.) TV.

For satellite platforms, photographic film pack ejection and recovery is practicable but not economically practical for the continuous transmission requirements of an operational ERS. Since this operational constraint requires real time (or near real time) transmission, then the digital format is most efficient for several reasons: communication efficiency (Pulse Code Modulation, etc), adaptable to computer or special purpose pre-processing, improved information quality through the removal of systematic errors (by digital means), signature detection by statistical means, format flexibility, data quality maintenance, etc.

Since detectability is enhanced by lineal continuity, contrast, and resolution, then the sensor quality measure should reflect these attributes. The modulation transfer function (MTF) of the imaging system and the sensitivity of the detector (signal to noise threshold limit) are the corresponding sensor attributes of interest.

Otto Schade shows (4, 16) that the vidicon approaches the absolute photon noise limit more closely than the best photographic film camera. For example, with a vidicon using an S-20 photomultiplier detector, compared to a camera with Plus-X film, at a mean exposure of 10^{-2}Lm-S/m^2 (Lumen seconds per square meter), the RBV has a <u>theoretical</u> resolving power of 1000 cycles/m.m. compared to the camera's 80 cycles/m.m. Also, the sensitivity of the RBV can be extended to extremely low exposures (about 10^{-6} Lm-S/m^2), but at the expense of resolving power (10 cycles/m.m.). Of course, the wider dynamic range (from selectable film speeds) of the camera allow it to be used for high contrast objects (greater exposure), so the camera's resolving power is currently the best for sun lit objectives. But at medium to low contrasts, the TV, and RBV are superior.

Again, considering the MIS need to manage information (as opposed to data), maximum use should be made of the faster digital techniques and computer algorithms. Edge enhancement, and contrast enhancement are two of these techniques which are particularly appropos to the TV and RBV format. Therefore, from a systems viewpoint, the RBV and TV is considered superior to the camera, although the latter will still be used for ERS development work. Cameras for coverage from aircraft are also sure to continue as an indispensable part of an overall system consisting of multi-spectral scanners and TV/RBV on satellites, plus cameras (and other sensors) on aircraft, plus special purpose "in situ" sensors.

Another technique, called boundary enhancement, allows correlation of different instruments. This is of course particularly important if rigorous and complex multi-spectral analysis is to be attempted. Since the RBV/TV format is readily adapted to this technique, and since the software can be "hardwired" into a special purpose pre-processor, areas of interest can be pre-filtered from the total field of view. This in turn can save on communications, but ready adaptability to system (MIS) requirements is the greatest advantage. Also, when integrated into a suitable ERS/MIS, the instrumentation spatial resolution requirement for data samples within the bounded area is reduced, since special statistical inference can be employed (for example: yesterday's cornfield is still there). That is, perhaps five to fifteen resolved data points can be sufficient for a bounded corn field (for example), whereas with conventional instrumentation (camera, etc.) the resolved elements needed are on the order of 10^3 to 10^4 for a corn field. The net result is that even for scenes where the illumination favors photography, these digitally compatable sensors can "trade" data processing for resolution improvement.

Then from a systems viewpoint, the RBV/TV digital format sensor has higher <u>systems resolution</u> than does the camera in all conditions of illumination.

To extend system capabilities, the most fruitful improvements can be be made by extending the capability of the system to correlate imaging over ever wider spectral bands. This is equivalent to saying that the system quality depends on its temporal and spatial stability, and depends on the extent to which the system can be accurately collimated and calibrated. We will return to this subject in the last section of this paper, where trends and the total framework of a global net is discussed as a logical outgrowth of these (above) ideas.

We should point out that improvement in sensor capabilities are approaching fundamental limits (see Otto Schade, 4, 16). It is impossible for a TV or RBV detector to be more sensitive than the photon noise limit, and direct spatial discrimination by analog means cannot exceed the Rayleigh criteria limit. Improvements can come mainly from increasing the aperture size (and sensor cost and satellite size and cost) up to the limit of practical construction, or by implementing new data processing ideas that are intimately "married" to the sensor. The synthetic aperture radar (5) is an outstanding example of the latter. But without exception, the improvements all depend on <u>coherent</u> techniques and sensors (lasers, interferometers, radar, doppler, synthetic aperture, etc.). Therefore, fundamental systems constraints that effect the coherence time, or the propagation delay or stability, are the most promising areas from which system improvements can come. We will examine a network, that accomodates these constraints, in the last section.

Progress is also being made in extending the determinational accuracy of the distribution of systematic errors in sensors. These techniques make use of regression analysis using impressive arrays of observational equations, since the error models are quite extensive. Of course, the more unknowns there are in a system of equations, the more equations are needed for a determination. This again points to the usefulness of multiple sensor/detector channels (for multi-spectral sampling of ERS species) as these supply the necessary data redundancy to assure determinancy for these rather massive regression analyses. That is, the multiple channels will not only improve the statistical reliability of correct species identification, but multiple channels also accomodates the computer calibration of the systems.

Theoretical Considerations

We can use Fourier transform methods to arrive at a power spectrum analysis. This will give us an analytic tool that is representative of contrast v.s. frequency (or wavelength), which is fundamental to the specie signature determination. To simplify our sensor system, we will represent it by its transfer function $T(f)$ (to be described), which is assumed to be the system transfer function.

In Figure 9 (following), we can represent the object radiance (across the scene in the x direction) as $o(x)$, which is depicted here as a wavy irregular line above the x axis. The image irradiance, $i\ (x)$ is also shown.

The power spectrum of $o(x)$ and $i(x)$ can be represented by the Fourier transforms $G_o(f)$ and $G_i(f)$:

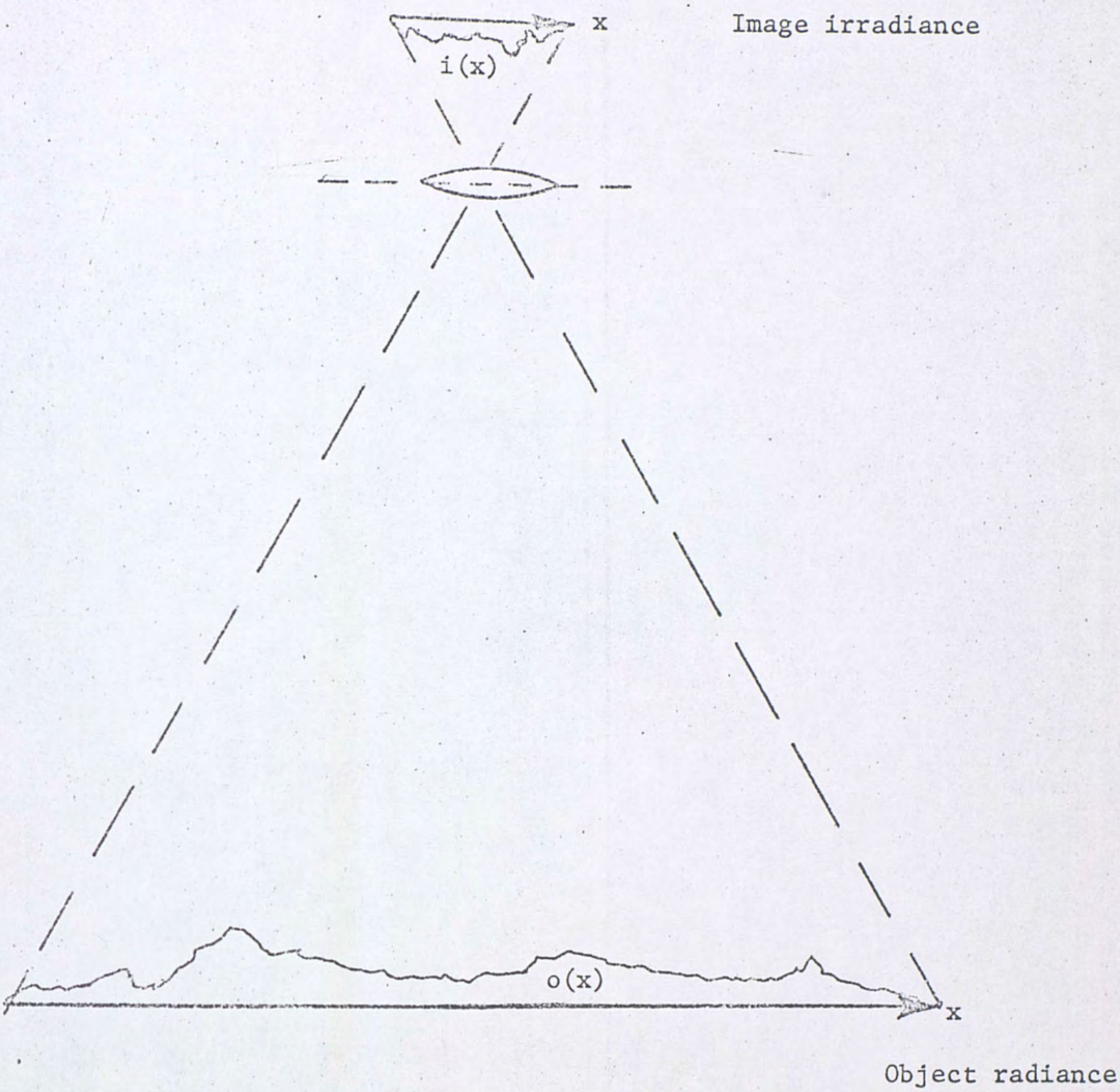

FIGURE 9. An Intensity Profile Along A Scan Line

$$G_o(f) = \lim_{L_o \to \infty} 1/L_o \left[\int_{-L_o/2}^{L_o/2} o(x) e^{-i2\pi xf} dx \right]^2 = \left[0(f) \right]^2$$

$$G_i(f) = \lim_{L_i \to \infty} 1/L_i \left[\int_{-L_i/2}^{L_i/2} i(x) e^{-i2\pi xf} dx \right]^2 = \left[I(f) \right]^2$$

Where x in the object is scaled by focal length/altitude; f is scaled by altitude/focal length: L_i and L_o are spatial extent; f is spatial frequency.

We assume the sensor system componenets to be time invariant, so we have the relation:

$$I(f) = T(f)\ 0\ (f)$$

with T(f) the sensor system transfer function.

To see the detected "power taper" v.s. frequency, we have taken the complex square (recalling G(f), I(f), 0(f), T(f) are complex expressions):

$$\left[I(f)\right]^2 = \left[T(f)\right]^2 \left[0(f)\right]^2$$

Substituting, we have:

$$G_i(f) = \left[T(f)\right]^2 G_o(f)$$

Then a frequency component f in the image plane is modified in strength by the square of the complex transfer function of the sensor system. For any finite system, the $G_i(f)$ tapers rapidly from low to high f, so that the sensor acts as a low pass filter. This is obvious, since any Fourier series of a real system is convergent (tapers), so that the fourier transform squared will taper even more.

Critical Commentary

From a signature analysis viewpoint, "better" discrimination can be achieved between signatures (more reliable) by using higher frequencies; but higher frequencies are most attenuated by [T]; therein lies an engineering compromise. Since noise is also more of a problem at higher f's, most analysts (at LARS, Purdue University for example) use only the middle frequency part of the pass band. Most analysts complain of systematic errors (biases) in the lower frequency part of the pass band, so this is filtered out digitally in the MIS's preprocessor filter. Needless to say, herein is an area for much work in sensor systems.

This paper addressed the bias determination in section II; these biases dominate low spatial and temporal frequencies. That is:

1. at high frequencies, noise errors predominate, so Gaussian statistics are valid, but [T] cuts off the upper limit.
2. at low frequencies, bias errors predominate, and gaussian statistics are not valid. An approach which uses a "fit" to a valid error model is indicated. [T] does not limit.

We can estimate sensor performance from satellite altitude, by using results from aircraft flying the same type of sensor at high altitude (17). In this case, $|T\text{atmosphere}|^2$ is the same for the satellite and aircraft cases, so we can show:

$$|T\text{satellite}|^2 = \frac{G_i \text{ (satellite)}}{G_i \text{ (aircraft)}} \; |T\text{sensor}|^2$$

From this simple equation, it is clear that we will need aircraft for enough spatial resolution, to satisfy most earth resource requirements for a "close look." However, the satellite image provides the key for image adjustment, correlation, and correction of non-linearities. Also, for large scale surveys, the satellite imagery will be adequate by itself. It seems clear, however, that both aircraft and satellite platforms will be required.

In the opinion of this writer, satellite coverage for an operational ERS should have these attributes to optimize the net's calibratability:

1. Continuous, to smooth out the data stream (2, 3, 19, 20) so that digital TV and RBV's can be used most effectively. Large scale regression analysis with orbital constraints requires continuity over a large area. Continuity assures imagery overlap for synoptic adjustment to a common datum, for rigorous photogrammetric block adjustment.

2. Redundant for triangulation, multi-lateration, etc. adjustment techniques, for stereo optic viewing, reliability (to see behind blocking clouds), and increased statistical sampling.

3. Symmetric or having balanced geometry to minimize the geometric dilution of precision factor. Ideally, satellites should be arranged at apexes of equilateral triangles over the target area(s). This also equalizes doppler vector magnitudes, and positional projections in the image plane.

4. Orthogonal orbits, so that biases in scanning photometers, RBV's and other sensors will be part of independent data sets, thereby facilitating error detection and removal. Components of doppler and polarization of the light transmitted to the sensor would thereby be orthogonal and so independent, and so capable of being separated.

5. Counter-rotating orbits, to offset sensor "smear" effects (8, 9) due to orbital motion, and provide identical focal points for sensor pairs operating in the doppler mode (synthetic aperture radar, etc. (5). Such an arrangement would allow for periodic matching of the field of view from different satellites, as they passed in close proximity, with identical lighting conditions, to facilitate signature adjustments to the lighting (1, 12). The [Tatmosphere] is identical at the time for the two sensor platforms, so that $[T_{sensor}]_1$ can be compared with $[T_{sensor}]_2$. (2, 17) The time of passing is a precise initialization point for regression analysis.

6. Satellite-to-Satellite Linking at Medium Altitude so that the coherence advantage of the atmosphere free satellite-to-satellite path can be used to maintain rigid time and frequency control of the net (for correlation of the coherently illuminated imagery). This requires sufficient altitude to assure that the earth's limb horizon does not block the path; but altitude

should be the minimum consistent maximum spatial resolution. Ideally, bi-static illumination will be used (one satellite illuminates for the other) as forward-to-side scattered and reflected energy is one or two orders of magnitude larger than back-scatter (as in radar). This requires intra-satellite links to maintain coherency for correlation detection. Also the links are needed to carry the truly tremendous ERS data stream around the globe via this all space path without burdening the limited RF spectrum within the atmosphere. Isolation from earth RF interference can be almost absolute, since at 57 to 60 ghz (for example), the atmosphere attenuation virtually eliminates interference from earth sources. The receiver sensitivity can be extreme for these cold space point to point links, if cold parametric receivers are also used. With atmosphere scintillation absent, and very low effective received temperatures possible, these links will be virtually noise free (for error free data transmission, stable coherent references, and an ultra precise mensurational datum base for overall calibration). See also the six arguments for increasing altitude at the end of Section II.

IV. THE SATELLITE NET

General

In sections II and III, we showed that the optimum global ERS, would need a satellite net that would optimize calibrability, in order to optimize detectability for the total system. We also reviewed certain characteristics that are the critical technical virtues of such a satellite net: redundancy, symmetry, orthogonality, coherent satellite-to-satellite linking (requiring at least a medium altitude), and counter-rotating orbits. The satellite-to-satellite linked net is needed to provide a globally continuous coherent electro-magnetic data base (for ERS calibration) and data transmission network (for the heavy ERS data stream). This is an unusually demanding requirement, and yet it is critical to the upgrading of the sensor data (through computer self calibration) for a viable ERS. Therefore, in this section we will describe such a net in sufficient detail to show that it is practical.

The ROSAE Concept

The six technical attributes prescribed for calibratability are also vital to the practical linking of satellites into a global communication and navigation network. In 1972, Duane Brown, President of DBA Systems, Incorporated, Melbourne, Florida, presented a proposal to the DOD joint communication/navigation satellite steering committee, that was based on a satellite net with these (same) key features. This net, known as the ROSAE concept, was invented by the author twelve years ago. (All patent rights are retained by the author under U.S. Patent No.

3,243,706).

As an aside, the author recognizes a potential reader credibility problem; the author naturally has a proprietary interest in the ROSAE concept. The reader is expected to be more detached, and to view the following as one of perhaps many potential proposals for a global network; however, the author will write of his own honest conviction that it is the optimum net.

Brown, an internationally recognized authority in photogrammetry and multi-laterrative regression analysis techniques (with extensive error modeling and comprehensive orbital constraints), was able to prove by computer simulation of the full ROSAE net, as a navigational framework, that conventional range and range rate links could be used to navigate aircraft to an accuracy of ten to one hundred centimeters. This was about two orders a magnitude better than the next best configuration tested by the simulation. Brown showed that ROSAE is optimum because the six technical attributes (section III) operated to give the net superior calibratability. Previously, the author had shown that the net was practical to establish and maintain (because of its use of resonant orbits), and that sat-to-sat communication links would be practical for the net (because of constant angular momentum tracking). In this section, we will look at the dynamics of the ROSAE net to appreciate the far reaching impact of these basic-technical virtues (redundancy, orthogonality, symmetry, etc.).

In order to net satellites together via electromagnetic links, practical energy conservation considerations almost force the satellite design into a highly directive beams. As with any directive electromagnetic radiator, the aperture should be a physical lense or antenna (for practical efficiency and reliability). This physical aperture has mass; to track the sat-to-sat motion, it must rotate in space and therefore it will generate an angular momentum vector. Ideally, the generation of this angular momentum will not consume much energy or cause disturbing gyroscopic effects. As we will show next (by a vector math analysis) all satellites in the net will track with constant angular momentum, without gyroscopic cross-coupling to disturb the satellite's attitude. With constant angular momentum, the antenna drives consume only enough energy to overcome friction. Furthermore, the tracking requirement from the satellite's viewpoint, is very simple; a common universal joint driven at twice the satellite's orbital rate, will track exactly as required.

The description that follows concerns a global network, so we should be careful to base our mental judgements on "complexity" and "cost" relative to other (comparative) global nets. Necessarily, a global multi-function net is large, complex, and costly. But income for a global ERS was estimated (in 1969) as "$billions annually," by the National Academy of Sciences. We should mentally overlay the communications and navigation services in addition to the ERS services, to form a rough idea of the enormous income that will accrue to such a network. Also, since complexity connotes technical difficulty, and so arouses questions concerning the viability of such a net, we should be careful to distinguish complexity at the satellite, as the critical area of technical feasibility. It does not necessarily follow that satellites are complex just because a net is complex. Similar comments can be directed toward orbital insertion, precise orbital station keeping, etc. The problems that constrain the net's technical feasibility are those as viewed from the satellite, not those from our (the reader's) viewpoint as we look at the complex network pattern (Figures 10 and 11). As we mentioned before, the tracking problem at the satellite is simple. Also, the network is the least complex of any global network capable of this link density. Furthermore, the use of resonant orbits, assures efficient and reliable orbital insertion of all of the satellites in the array. However, the scope of this paper excludes a detailed discussion of these resonant orbits.

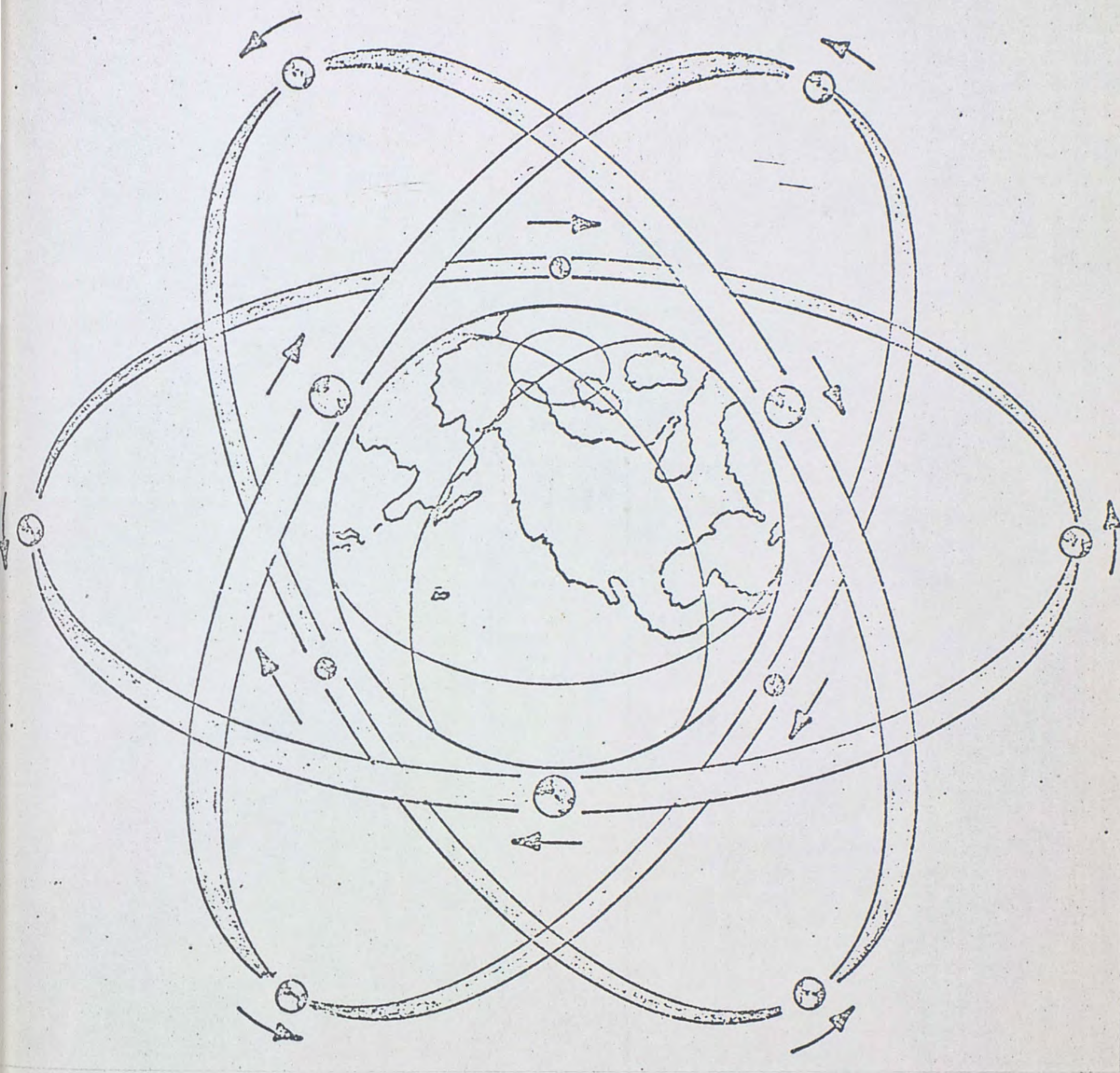

FIGURE 10. The Geometrically and Dynamically Balanced
ROSAE Satellite Array

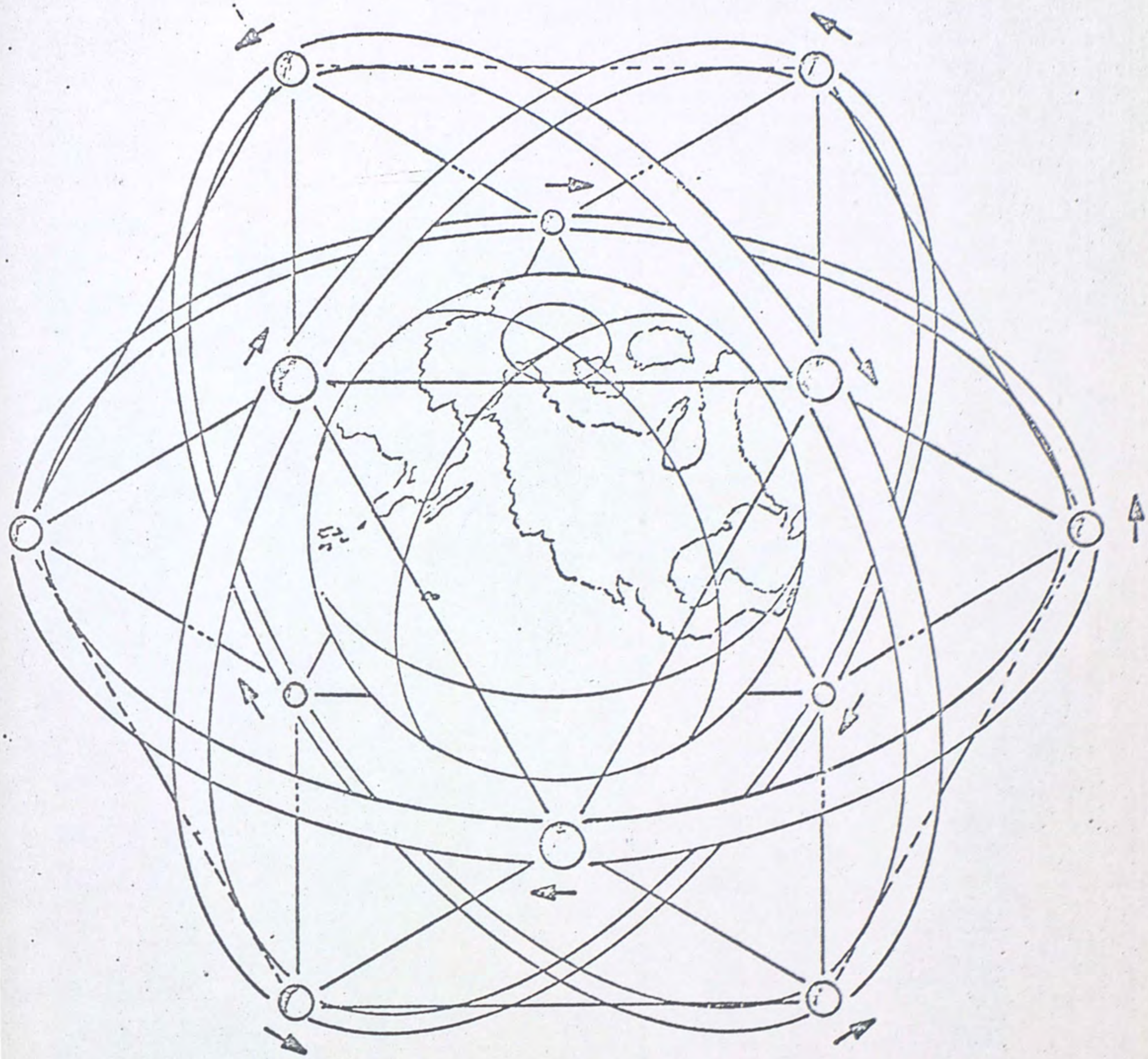

FIGURE 11. A Balanced Global Net That Affords Simple Intra-Satellite Tracking

In Figure 10 the satellite array is shown at a point in time when the satellite epochs are midway between the phase where they "meet" (pass at the point of closest approach). Present velocity is indicated by small arrows. For perspective, the three nearest satellites are shown as the largest (on top). The three smallest sized satellites are "far" (on the bottom). In between, are six medium sized satellites on the outer edge of the pattern. The three orbital planes are mutually perpendicular, forming an orthogonal set. Two of these orbital planes are polar, the remaining one is equatorial. Notice how the satellites simultaneously converge (then diverge) at the six intersections of the orbital planes. Of course, in an operational net, epochal precision would not have to be so extreme as to require even a remote probability of collision at these "meetings".

Inertial Stability Of The Net

The three orbital planes intersect at X, Y, Z in Figure 12. Axis Z coincides with the geoidal angular momentum vector, and is fixed inertially (for all practical purposes, we can ignore the small geoidal precessions). Since the orbits are resonant, i.e., their angular velocity, ω_o, is five times the earth's angular velocity, and the perturbational history of the polar orbits is cyclical. Therefore, the polar orbits will not precess under the influence of gravitational anomalies. The orbital planes and their corresponding intersection X, Y are inertially fixed. Since X, Y, Z is an inertially fixed orthogonal triad, if we use this earth centered inertial triad as our reference in the following dynamic analysis, we will have an inertially referenced dynamic description. It is most important that we explore the dynamics initially in an inertial frame, as this is the frame of reference for Newtonian physics, and we want to explore energy and stability criteria against these fundamental laws. After getting an inertially referenced dynamic analysis, we will want to explore the satellite dynamics in a rotating coordinate system, as the satellites will all have a constant pitch rate equal to ω_o (to keep their sensors pointing earthward).

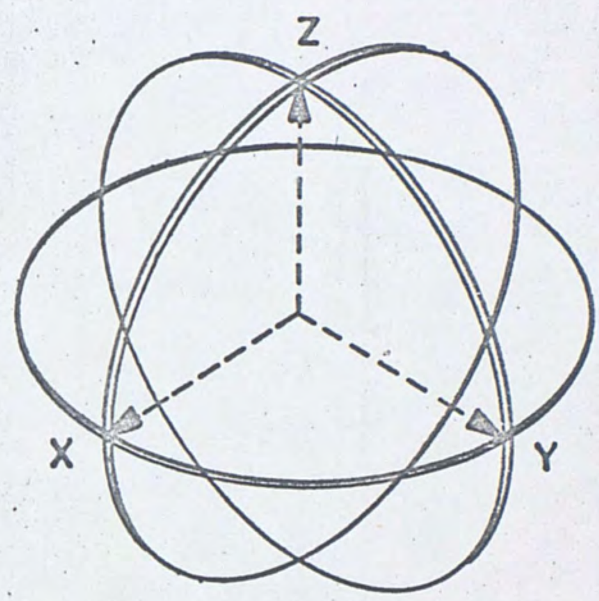

FIGURE 12. Orthogonal Orbits Needed For Orthogonal Net

We note also that the use of resonant orbits lends stability to the in-plane orbit ephemeride terms. This is the "natural station-keeping" torque provided by the more dominant anomalies in the earth's gravity field, when resonant orbits are employed. Since our present concern is beam motion dynamics, we will not discuss "natural station-keeping" here, but for a comparison, the resonant orbit used by ROSAE permits a ten fold improvement over the station-keeping accuracy of the well known synchronous orbit concept.

Satellite-To-Satellite Beam Motion Dynamics (Inertially Referenced)

We are only interested here in the dominant energy and motional requirements on the beam tracking. Since the high gain beamwidths will not have to be narrower than 3^{o} to 30^{o} in even the most ambitious design, we can ignore many small effects. Orbital errors and most tracking motion errors will be negligible in view of these anticipated beamwidths. Therefore, although we will base our analysis on a "perfect" pattern for ROSAE (epochs are matched, all orbits are precisely orthogonal, etc.), this is not necessary for an operational net. Relative to the synchronous concept, this net will be twenty times less sensitive to these errors.

In Figure 13, we show a pair of satellites a, and b. Here we assume that a is tracking b, so that we are interested in the tracking dynamics as seen from an inertial reference centered at a's center of gravity. From 0, we form two vectors $\hat{a}$ and $\hat{b}$ as shown, so that the desired beam motion is that for $\hat{r}$, where:

$$\hat{a} + \hat{r} = \hat{b}$$

$$\hat{r} = \hat{b} - \hat{a}.$$

Then $\hat{r}$ is the position vector of "b" relative to "a", and $\dot{\hat{r}}$ will be the relative velocity, etc., yet the reference remains inertial.

Since the orbital angular velocity equals ω_o, then we can "initialize" or start from some time τ_o (at the last "meeting" just prior to this present epochal view) and so the epochal phase of each satellite is $\omega_o\tau$ as shown in the figure. Since $\hat{a}$ varies sinusoidally in the Y, Z plane, and $\hat{b}$ in the X, Y plane, then we have:

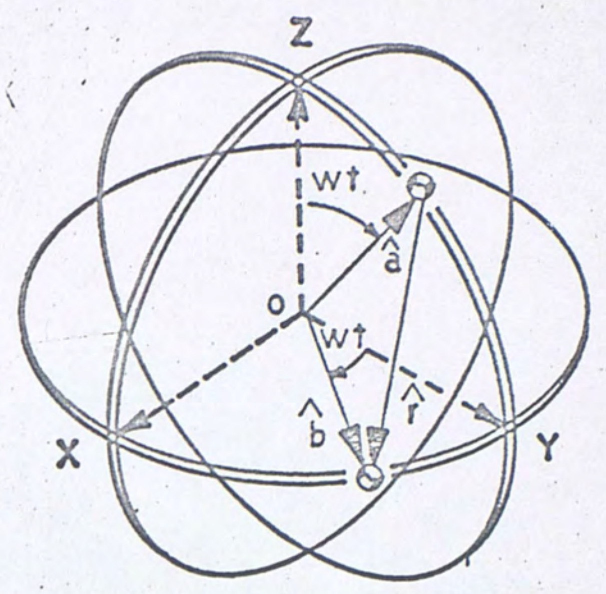

FIGURE 13. Relative Position Vector For Intra-Satellite Links

$$\hat{a} = \rho_o \begin{pmatrix} 0 & \hat{i} \\ \sin\omega_o\tau & \hat{j} \\ \cos\omega_o\tau & \hat{k} \end{pmatrix}$$

$$\hat{b} = \rho_o \begin{pmatrix} \sin\omega_o & \hat{i} \\ \cos\omega_o\tau & \hat{j} \\ 0 & \hat{k} \end{pmatrix}$$

where ρ_o is the common radius of these nominally circular orbits (ignoring perturbations). Note: $\rho_o^3 = \dfrac{\gamma}{\omega_o^2}$, where γ is the gravitational constant.

$$\hat{r} = \hat{b} - \hat{a} = \rho_o \begin{pmatrix} \sin\omega_o\tau & \hat{i} \\ (\cos\omega_o\tau - \sin\omega_o\tau) & \hat{j} \\ -\cos\,\omega_o\tau & \hat{k} \end{pmatrix}$$

we also find the time derivative, or velocity of $\hat{r}$:

$$\dot{\hat{r}} = \dot{\hat{b}} - \dot{\hat{a}} = \rho_o \omega_o \begin{pmatrix} \cos\omega_o\tau & \hat{i} \\ (-\sin\omega_o\tau - \cos\omega_o\tau) & \hat{j} \\ \sin\omega_o\tau & \hat{k} \end{pmatrix}$$

We are immediately interested in the angular momentum, $\hat{M}$ (a vector), and the kinectic energy, T (a scalar), so we determine a "massless" $\hat{M}$:

$$\hat{M} = \hat{r} \times \dot{\hat{r}} = \rho_o^2 \omega_o \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ (\sin) & (\cos-\sin) & (-\cos) \\ (\cos) & (-\sin-\cos) & (\ \sin) \end{vmatrix}$$

which reduces to:

$$\hat{M} = \rho_o^2 \omega_o \begin{pmatrix} -1 & \hat{i} \\ -1 & \hat{j} \\ -1 & \hat{k} \end{pmatrix} \quad \text{and} \quad |\hat{M}| = \sqrt{3}\ \ \rho_o^2 \omega_o$$

Then $\hat{M}$ is inertially fixed in magnitude and direction, and so the total energy is also constant.

In Figure 13, since the view is an isometric drawing, X, Y, Z are equally spaced from the normal to the plane of the paper:

$$\begin{pmatrix} +1 & \hat{i} \\ +1 & \hat{j} \\ +1 & \hat{k} \end{pmatrix}$$

Then we see that $\hat{M} = \rho_o^2 \omega_o \begin{pmatrix} -1 & \hat{i} \\ -1 & \hat{j} \\ -1 & \hat{k} \end{pmatrix}$ is directed down, normal to the plane of the paper. From classical mechanics, we know that the plane that is normal to $\hat{M}$, is the invariant plane. Then the invariant plane is the plane of the paper. Then $\hat{r}$ and $\dot{\hat{r}}$ move in a plane parallel to the plane of the paper. Although this plane translates with satellite "a", "up" and "down" along the M direction, this does not effect $\hat{r}$, $\dot{\hat{r}}$, or $\hat{\omega}$ since these are relative position, velocity vectors from "a".

Multiple Link Geometry

The previous description concerned a single link between satellites in different orbital planes. We are interested particularly in such linkage as the data is "cross plane" rich. However, a brief consideration of Figure 9 shows that links between different orbital planes are the most practical links, since the earth's limb would interrupt links between coplanar satellites. Cross plane links could be maintained continuously; they could have "infinite" acquisition time; the doppler embedded in the data can be isolated since it will be orthogonally related.

Then we are interested in forming a network out of links between the satellites in different orbital planes (just as we did in our previous analysis). Since there are eight satellites in the "different" orbit planes, then a maximum of eight intra-satellite links are available. But since balanced geometry is an ingredient for a good calibration and navigational potential as well as efficient communications netting, we should consider a balanced network for this linkage.

We begin by considering a second link from "a" in Figure 12 to the satellite that is opposite to "b" in Figure 12. This double linked configuration is shown in Figure 14.

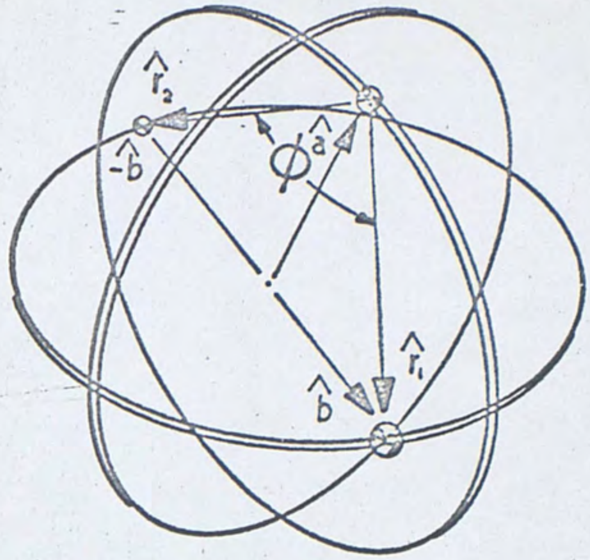

FIGURE 14. Double Linking For Balanced Moments

Since the second satellite is 180° in orbit from the first "b", then we can represent its position as -b. Then we have:

$$\hat{r}_1 = \hat{b} - \hat{a}$$

$$\hat{r}_2 = -\hat{b} - \hat{a}.$$

Our next interest concerns the angle that exists between $\hat{r}_1$ and $\hat{r}_2$, since this will have a direct impact on the physical structure of our satellites (represented by "a" here).

We form the dot product between $\hat{r}_1$ and $\hat{r}_2$ (recalling the magnitudes of $\hat{a}$ and $\hat{b}$ are the same, i.e. ρ_o), $|\hat{r}_1|\ |\hat{r}_2| \cos \Phi = \hat{r}_1 \cdot \hat{r}_2 =$ $(\hat{b} - \hat{a}) \cdot (-\hat{b} - \hat{a}) = (-\hat{b} \cdot \hat{b}) + (\hat{b} \cdot -\hat{a}) + (-\hat{a} \cdot -\hat{b}) + (-\hat{a} \cdot -\hat{a})$.

Since the 2nd and 3rd terms cancel, we have:

$$= -b^2 + a^2 = -\rho_o^2 + \rho_o^2 = 0 \quad \text{or} \quad \cos\Phi = 0.$$

Then $\Phi = 90^{\circ}$ (at all times), so that a fixed antenna structure at the satellites is practical, that will handle two links at a time. Actually, this result could be surmised from a brief consideration of plane geometry. Since the three satellites in Figure 14 are in a plane

(3 points determine a plane) that contains the origin (b is 180° from -b), then this plane is a great circle, and "a" is the apex of a triangle inscribed in a semicircle. From plane geometry, we know that such a triangle is always a right triangle, i.e., $\Phi = 90^{\circ}$.

A fixed antenna structure with beams 90° apart is most practical for a pair of high gain antennas, such as a pair of small "dishes" oriented on orthogonal axes. High gain directed apertures are apropos to the multi-function use of the ROSAE network, where large bandwidth signals will be transmitted over the intra-satellite communication net and for a navigation network using ranging techniques. Then we need to discuss the implications of the geometry and dynamics on multiple linking with a "rigid body" 90° antenna structure.

Multiple Link Dynamics

By a method similar to that used above we find:

$$\hat{M}_2 = \rho^2 \omega_o \begin{pmatrix} -1 & \hat{i} \\ +1 & \hat{j} \\ -1 & \hat{k} \end{pmatrix}$$

and,

$$\hat{\omega}_2 = \frac{\rho_o^2 \omega_o}{r_2^2} \begin{pmatrix} -1 & \hat{i} \\ +1 & \hat{j} \\ -1 & \hat{k} \end{pmatrix}$$

Clearly these axes are not orthogonal to the $\hat{M}_1$, $\hat{\omega}_1$ axes, since the direction cosine (the dot product) does not vanish:

$$1/\sqrt{3} \begin{pmatrix} -1 \\ +1 \\ -1 \end{pmatrix} \cdot 1/\sqrt{3} \begin{pmatrix} -1 \\ -1 \\ -1 \end{pmatrix} = 1/3\ (+1\ -1\ +1) = 1/3.$$

However, the combined "rigid body" structure will have a constant angular momentum $\hat{M}_{1,2}$ of:

$$\hat{M}_{1,2} = \rho_o^2 \omega_o \begin{pmatrix} -1 \\ -1 \\ -1 \end{pmatrix} + \rho_o^2 \omega_o \begin{pmatrix} -1 \\ +1 \\ -1 \end{pmatrix}$$

$$\hat{M}_{1,2} = \rho_o^2 \omega_o \begin{pmatrix} -2 \\ 0 \\ -2 \end{pmatrix} = 2\rho_o^2 \omega_o \begin{pmatrix} -1 & \hat{i} \\ 0 & \hat{j} \\ -1 & \hat{k} \end{pmatrix}$$

Let us form a rather dense network consisting of four links per satellite, similar to Figure 11, but let us minimize the dynamic and mechanical problems. Let us pick a configuration with dynamic balance, that also has the 90^o beam separation feature, and so only two moving antenna mounts. One of these is shown in Figure 15. Since M_x components (in the $\hat{i}$ direction) are supplied by the satellite's pitch, and the remaining components are equal but opposite, then the action of one mount will cause an equal but opposite reaction on the other mount as desired. Then a single torquing device is required. We should emphasize that this means one control device (impulse source) is needed to periodically replace frictional losses. Then only one simple mechanism is needed for four beams! We will show this next.

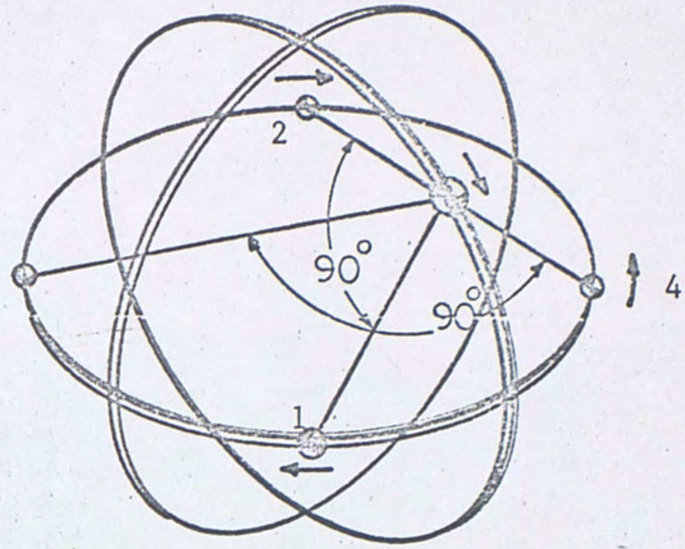

FIGURE 15. Configuration With Balanced Moments and Dynamics

Angular Velocity, $\hat{\omega}_{RB}$, Of The Double Beam "Rigid Body"

In Figure 15, we introduced an "optimum" antenna mounting geometry, with the fewest moving parts per beam. One of these beam pairs is shown in Figure 16a below, with the associated vector velocities $\dot{\hat{r}}_1$ and $\dot{\hat{r}}_2$. We can show $\dot{\hat{r}}_1$ and $\dot{\hat{r}}_2$ are orthogonal, since $\dot{\hat{r}}_1 \cdot \dot{\hat{r}}_2 = 0$. Then we can form an orthogonal body axes set (triad):

$$\dot{\hat{1}} = \frac{\dot{\hat{r}}_1}{\dot{r}_1}, \quad \dot{\hat{2}} = \frac{\dot{\hat{r}}_2}{\dot{r}_2}, \quad \dot{\hat{3}} = \dot{\hat{1}} \times \dot{\hat{2}}.$$

We have the required tracking dynamics:

$$\hat{\omega}_{RB} \times \hat{r}_1 = \dot{\hat{r}}_1$$

$$\hat{\omega}_{RB} \times \hat{r}_2 = \dot{\hat{r}}_2 .$$

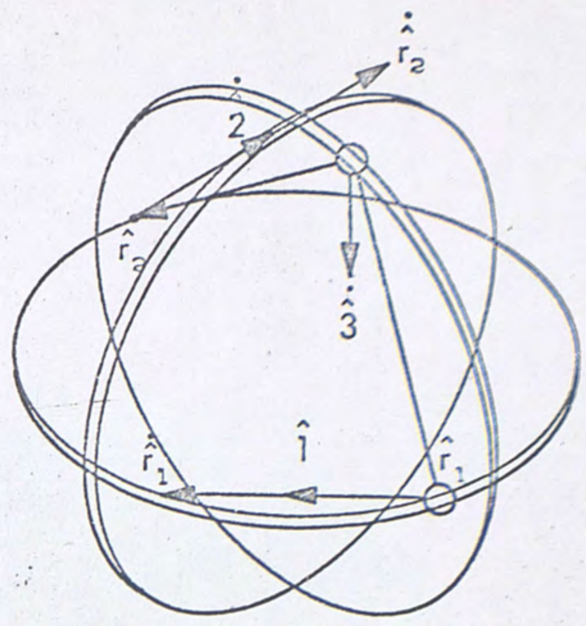

FIGURE 16a. Relative Positions For Angular Velocity Reference

Then from the definition of vector cross products, $\hat{\omega}_{RB}$ must be orthogonal to both $\dot{\hat{r}}_1$ (or $\dot{\hat{1}}$) and $\dot{\hat{r}}_2$ (or $\dot{\hat{2}}$); therefore, $\hat{\omega}_{RB}$ must be in the $\dot{\hat{3}}$ direction (Figure 16b).

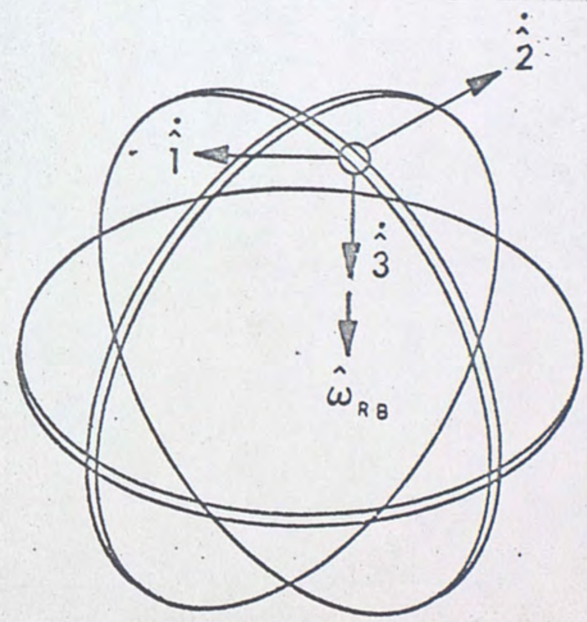

FIGURE 16b. Angular Velocity Direction

$$\dot{\hat{3}} = \dot{\hat{1}} \times \dot{\hat{2}} = \frac{\dot{\hat{r}}_1}{\dot{r}_1} \times \frac{\dot{\hat{r}}_2}{\dot{r}_2} = (4 - \sin^2 2\omega\tau)^{-\frac{1}{2}} \begin{pmatrix} -2\sin^2\omega\tau & \hat{i} \\ -2\sin\omega\tau\cos\omega\tau & \hat{j} \\ -2\cos^2\omega\tau & \hat{k} \end{pmatrix}$$

We can find the magnitude, ω_{RB}, from the kinectic energy, T:

$$T = \tfrac{1}{2}\hat{\omega}_{RB} \cdot \hat{M}_{1,2} = \tfrac{1}{2}(\omega_{RB}\cos\gamma)\ (2\sqrt{2}\rho_o^2\omega_o);$$

also we have

$$T = \tfrac{1}{2}\Sigma\dot{r}_1^2 + \dot{r}_2^2 = 2\rho_o^2\omega_o^2 \quad = \underline{\text{constant}}\ \text{(see *Note)}$$

$$\cos\gamma = \dot{\hat{3}} \cdot \frac{\hat{M}_{1,2}}{M_{1,2}} = \left(\frac{2}{4 - \sin^2 2\omega\tau}\right)^{\frac{1}{2}}$$

$$\omega_{RB} = \frac{2T}{M_{1,2}\cos\gamma} = \omega_o(4 - \sin^2 2\omega_o\tau)^{\frac{1}{2}}$$

$$\hat{\omega}_{RB} = \omega_{RB}\ \dot{\hat{3}} = \omega_o \begin{pmatrix} -1 + \cos 2\omega_o\tau & \hat{i} \\ -\sin 2\omega_o\tau & \hat{j} \\ -1 - \cos 2\omega_o\tau & \hat{k} \end{pmatrix}$$

*Note: T = constant, is a very crucial finding; this proves that minimal energy is needed for the tracking, i.e., to compensate for friction losses only.

The Hodograph Of The Rigid Antennae Body

Since $\hat{M}_{1,2}$ is constant, $\hat{\omega}_{RB}$ will have a constant component, $\hat{\omega}_z 1$, in the $\hat{M}_{1,2}$ direction:

$$\hat{\omega}_z 1 = \hat{\omega}_{RB} \cdot \frac{\hat{M}_{1,2}}{M_{1,2}} = \omega_{RB}\cos\gamma = \sqrt{2}\ \omega_o = \text{constant.}$$

If we project ω_{RB} in the (X', Y', Z') reference frame where $\omega_{z'}$ is constant, we can see the motional dynamics more clearly. We form a rotation matrix:

$$[R'] = \begin{bmatrix} \text{Rotation of} \\ +45^{o} \text{ about Y} \end{bmatrix} = \begin{bmatrix} \cos 45^{o} & 0 & -\sin 45^{o} \\ 0 & 1 & 0 \\ -\sin 45^{o} & 0 & \cos 45^{o} \end{bmatrix}$$

$$\hat{\omega}^{1}_{RB} = [R']\,\hat{\omega}_{RB} = \omega_{o} \begin{pmatrix} \sqrt{2}\cos 2\omega_{o}\tau & \hat{X}' \\ -\sin 2\omega_{o}\tau & \hat{Y}' \\ -\sqrt{2} & \hat{Z}' \end{pmatrix}$$

In the X'Y' plane (the invariant plane of $\hat{M}_{1,2}$) we note:

$$\omega^{2}_{x'y'} = \omega^{2}_{x'} + \omega^{2}_{y'} = 2\omega_{o}^{2}\cos^{2}2\omega_{o}\tau + \omega_{o}^{2}\sin^{2}2\omega_{o}\tau.$$

Then since we also have $\cos^2 + \sin^2 = 1$, we have:

$$\frac{\omega^{2}_{x'}}{2\omega^{2}_{o}} + \frac{\omega^{2}_{y'}}{\omega^{2}_{o}} = 1.$$

This is an ellipse, with a major axis, a, and minor axis, b:

$$a = \sqrt{2}\omega_{o}$$

$$b = \omega_{o}.$$

Then we conclude that the trace of $\hat{\omega}_{RB}$ (it's hodograph) in space, is the elliptical cone shown in Figure 17. In classical mechanics terminology, we would call this the "space cone". We can expect a moving "body cone" to roll about the fixed "space cone", with $\hat{\omega}_{RB}$ being the tangent line between the "cones".

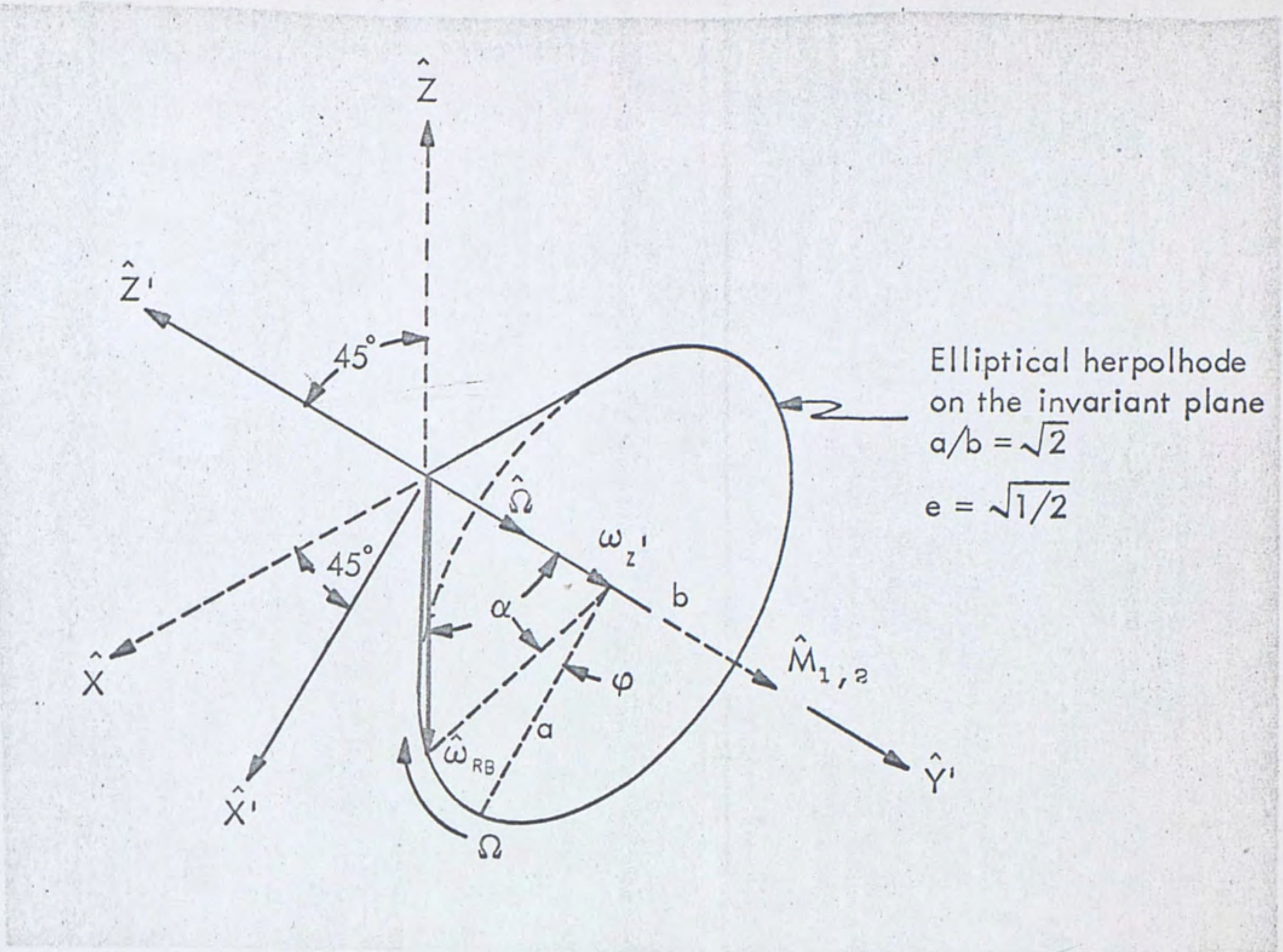

FIGURE 17. The Elliptical Cone Trace (Hodograph) of $\hat{\omega}_{RB}$

Since the precession, $\hat{\Omega}$, has an angular velocity about Z' as shown, with a right handed screw sense in the direction of $\hat{\omega}_{z'}$, then the precession is direct (positive). We find:

$$\tan \phi = \frac{\omega_{y'}}{\omega_{x'}} = \sqrt{\tfrac{1}{2}} \tan 2\omega_o \tau$$

Taking derivatives of both sides, we find:

$$\dot{\phi} = \Omega = \frac{2\sqrt{2}\omega o}{1 + \cos^2 2\omega\tau} = \frac{4\sqrt{2}\omega o}{3 + \cos 4\omega_o \tau} .$$

A Very Simple Tracking Mechanism

The previous motional requirement is an intriguing result, since we can again generate the identical dynamic motion with a Hooke's joint (universal joint), which is the simplest two degree of freedom device. We have from Figure 18, and spherical trigonometry: $\tan\phi = \tan\theta\cos\delta$. For input conditions:

$$\theta = 2\omega_o\tau,$$

or a constant rate twice the orbital rate (ω_o), and,

$$\delta = 45^o$$

$$\tan\phi = \sqrt{\tfrac{1}{2}}\,\tan 2\omega_o\tau.$$

Then the output must be Ω (exactly). In short, the seemingly complex motion of Figure 17 is actually simple to generate (Figure 18).

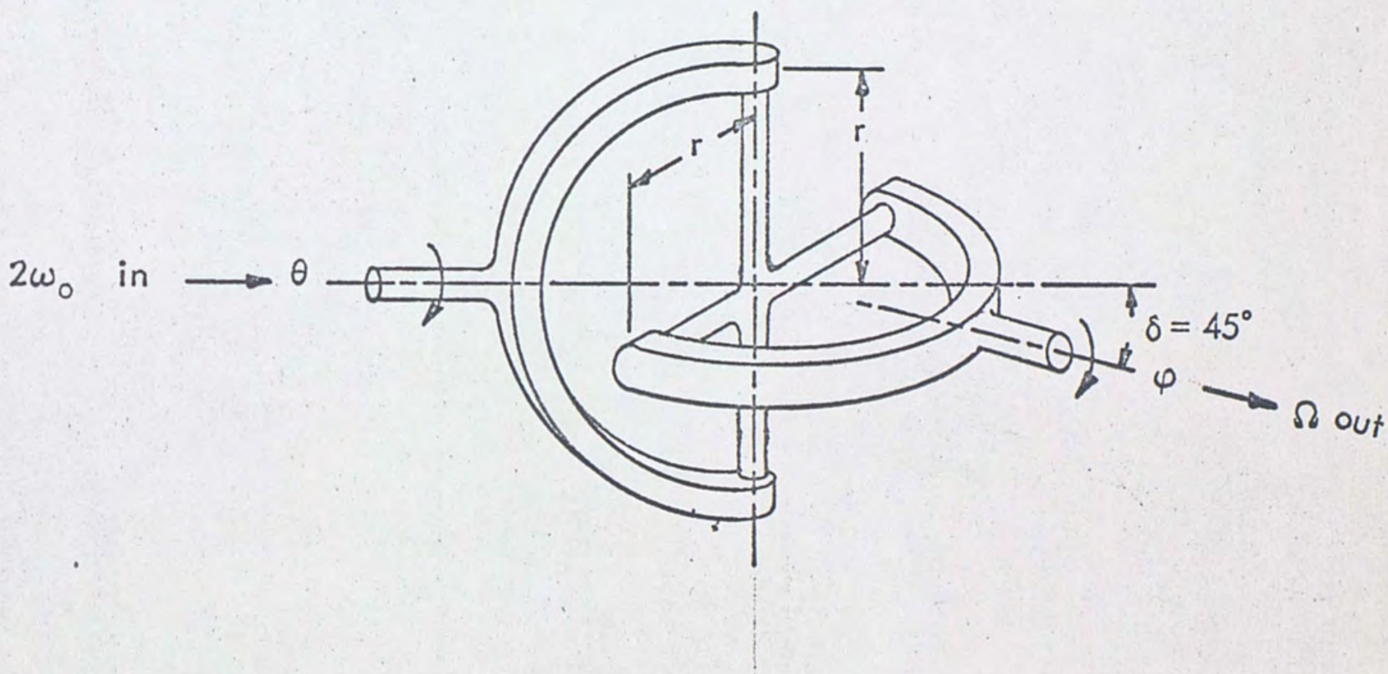

FIGURE 18. A Hooke's Joint (Universal Joint)

Gyroscopic Coupling Compatability

Since the satellite must maintain a "belly down" altitude in order to keep its sensors pointing earthward, the satellite itself generates a comparatively large angular momentum vector in the direction perpendicular to its orbital plane ($\hat{i}$ direction for satellite "a" in Figures 13, 14, 15) we showed:

$$\hat{M}_{1,2} = 2\rho_o^2\omega_o \begin{pmatrix} -1 & \hat{i} \\ 0 & \hat{j} \\ -1 & \hat{k} \end{pmatrix}$$

For the other rigid body (paired antennas) we have:

$$\hat{M}_{3,4} = 2\rho_o^2\omega_o \begin{pmatrix} -1 & \hat{i} \\ 0 & \hat{j} \\ +1 & \hat{k} \end{pmatrix}$$

Next, we see that the total angular momentum for the four antennas sums in the same direction ($\hat{i}$) as the satellite, so that gyroscopic cross coupling is zero:

$$\hat{M}_{total} = \hat{M}_{1,2} + \hat{M}_{3,4} = 4\rho_o^2\omega_o \begin{pmatrix} -1 & \hat{i} \\ 0 & \hat{j} \\ 0 & \hat{k} \end{pmatrix}$$

Zero gyroscopic cross coupling assures that satellite attitude will not be disturbed by the antenna motion. This minimizes the need for inertia wheels, attitude thrust correction, etc. and so conserves the precious satellite resources.

We conclude that we can track <u>four</u> satellites at a time, as in Figure 15, with <u>two</u> rigid antenna structures driven by simple universal joints at a constant angular velocity of $2\omega_o$. Furthermore, since each structure is identical but moving in opposite directional sense, only <u>one</u> motive force is needed to generate the action-reaction dynamics of the two identically matched antenna bodies. Then <u>one</u> constant drive motor is needed to precisely control <u>four</u> antennas (or lasers?)! Hopefully, the reader appreciates now that despite the forbidding aspect, of the global net when viewed in its entirety (Figure 11), the satellite's technical problems are minimal. Again, technical viability of such a concept is mostly a function of <u>satellite</u> complexity, not netting complexity, since the latter can be easily controlled by a computer.

Conclusions

Reviewing the findings of this paper:

1. The global ERS mission is fundamentally a management information system (MIS).

2. Species signature detection performance, or detectability, is the first order objective of the ERS/MIS.

3. Detectability is limited more severely by data biases from sensor non-linearities, than from spatial resolution, since the specie signature distribution is assumed to have a Gaussian distribution by the more advanced techniques. Also, the signature is a function of wavelength v.s. contrast (instead of spatial shape, etc.), so that the diffraction limit does not constrain ERS sensors (as much as it does conventional optics).

4. An optimum ERS has optimum detectability; therefore it has the least residual biases in the data; therefore it is optimally calibratable.

5. An optimally calibratable ERS will require a global control satellite net.

6. The satellite net will have certain features to assure a best calibration potential:

a. Redundant data channels.

b. Independent data channels, which specifies orthogonal orbits.

c. Strong geometric "leverage", which specifies a symmetric net.

d. Accurate time v.s. orbit epoch initialization, which specifies counter-rotating orbits.

e. Noise free data channels and noise free coherence reference to maximize coherence time, which specifies links outside the atmosphere for base reference, which specifies sat-to-sat links.

f. Continuous coverage and linking of all channels, which specifies a medium altitude.

7. The ROSAE concept meets these criteria; it is also a communications and navigation net.

8. The ROSAE concept is technically practical; merging the three functions (ERS, communications, and navigation) would be economically practical.

9. A global ERS/MIS is now technically and economically viable (it will require a national commitment; but our economy may <u>demand</u> it).

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